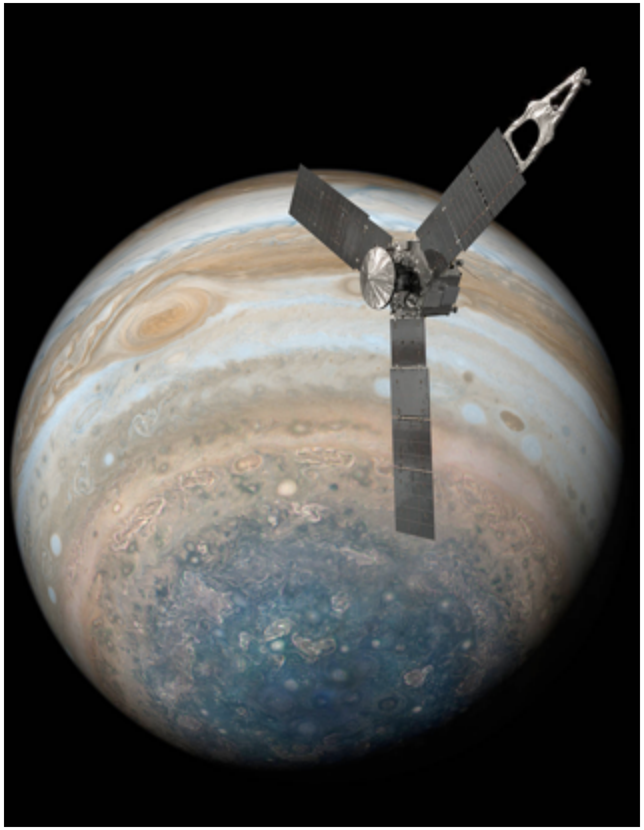
Radiated Electric and Magnetic Field Emissions Mitigations



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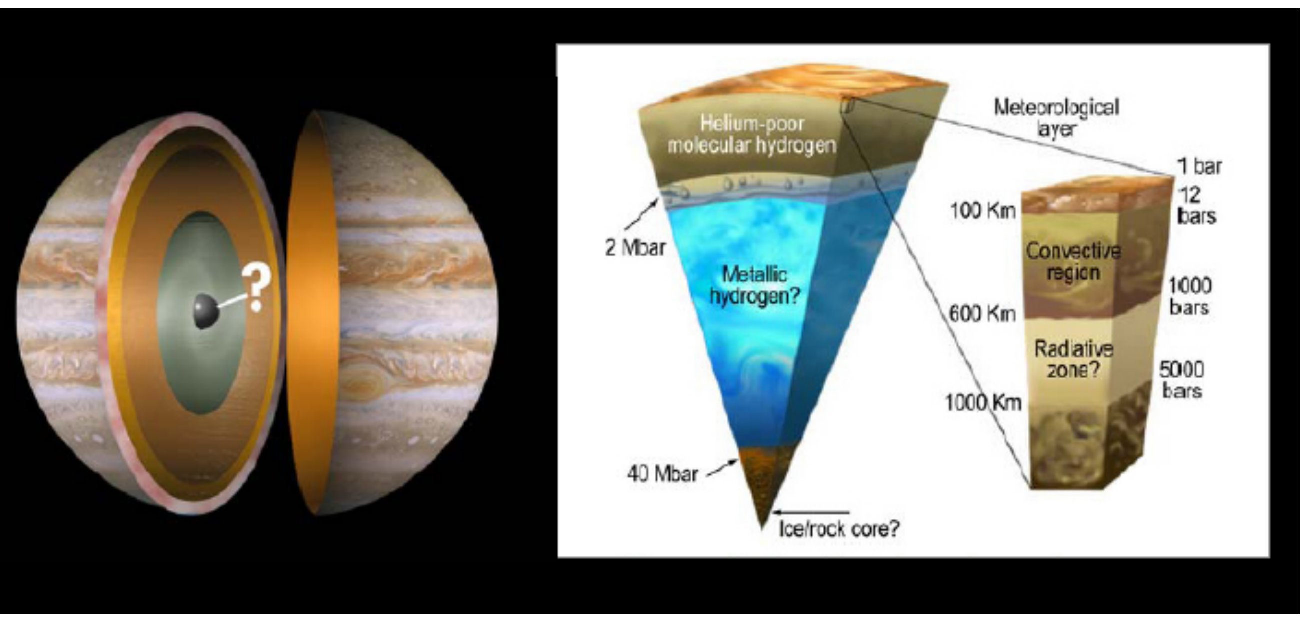
The JUNO Spacecraft- Instruments

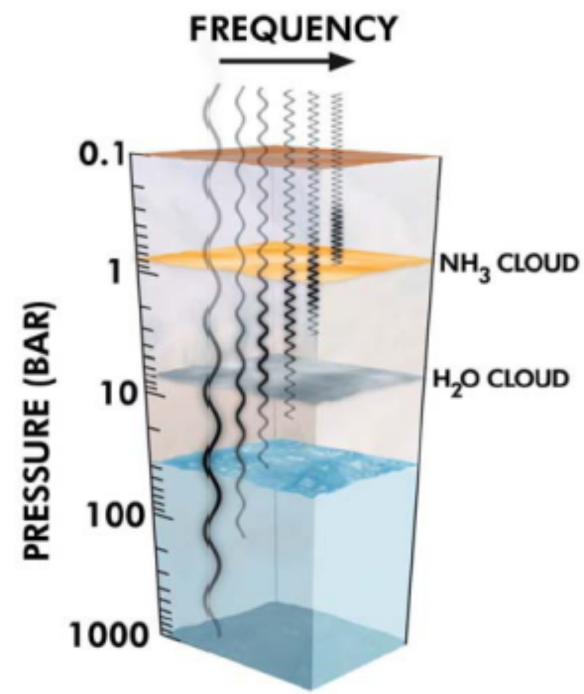
- JUNO Mission
  - NASA mission was launched in Aug 5, 2011, successfully entered Jupiter's orbit last year on July 4th, 2016.
  - Primary scientific goal is to improve our understanding of formation, evolution and interior structure of Jupiter
  - Juno mission carries nine instruments (some with multiple sensors)
    - Two Magnetometers, Gravity Science experiment, Jupiter Energetic Particle Detector Instrument (JEDI), Jovian Auroral Distributions Experiment (JADE), **Microwave Radiometer (MWR),** plasma instrument WAVES measures radio and plasma waves, The Ultra Violet Spectrogram (UVS), (JIRAM) Jovian Infrared Auroral Mapper, JUNOCAM is to photograph Jupiter's clouds.

JUNO Spacecraft (Courtesy of NASA)

The JUNO Spacecraft - MWR

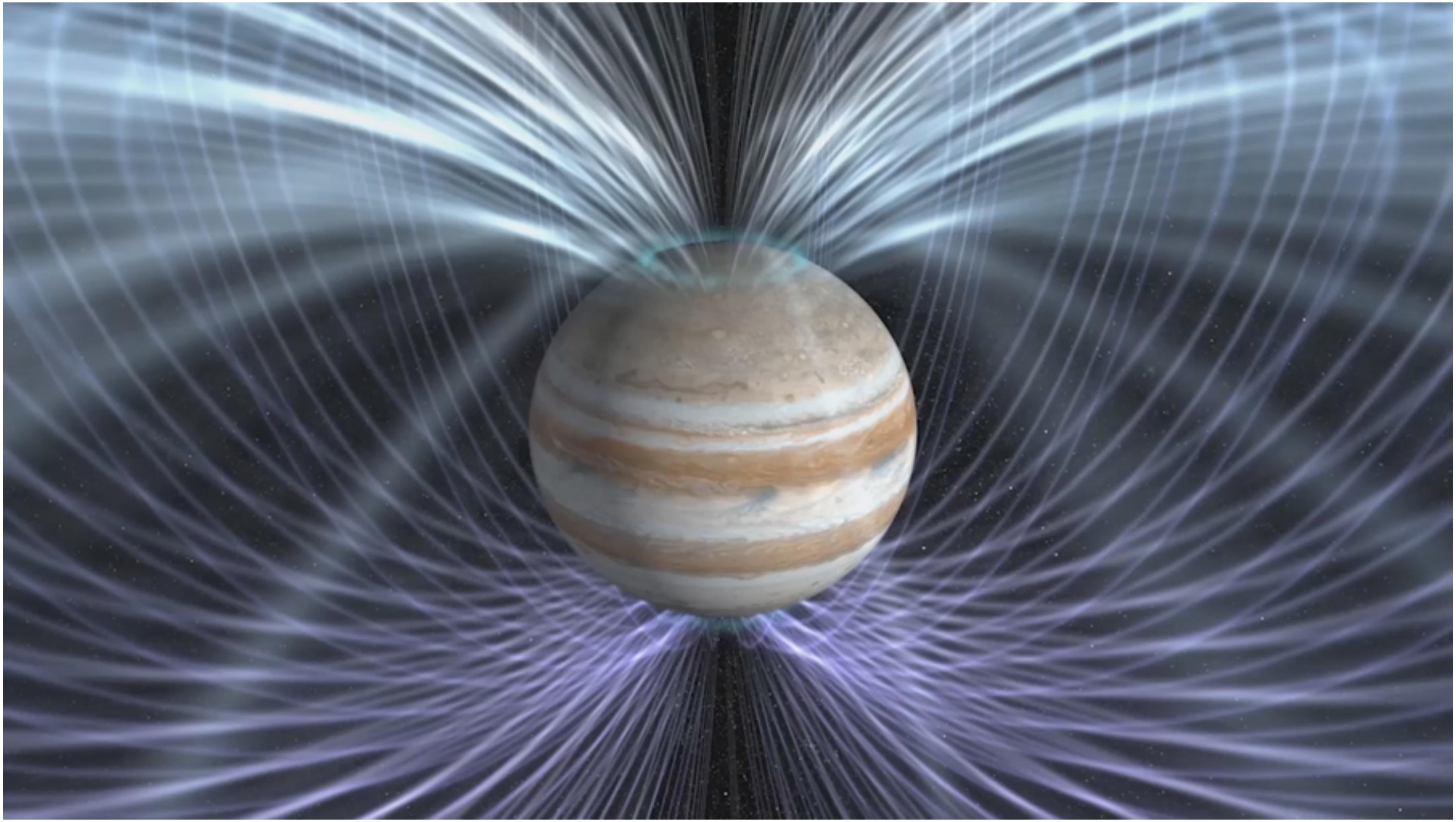
- JUNO Microwave Radiometer (MWR):
  - JUNO's MWR peers below the dense cover of clouds to answer questions about the gas giant and the origins of our solar system.
  - MWR measures thermal radiation from the atmosphere to as deep as 1000 atmospheres pressure (~500–600 km below Jupiter's visible cloud tops).
  - Determines water (H_2O) and ammonia (NH_3) abundances in the atmosphere all over the planet.





JUNO Spacecraft (Courtesy of NASA)

Jupiter's Strong Magnetic Fields

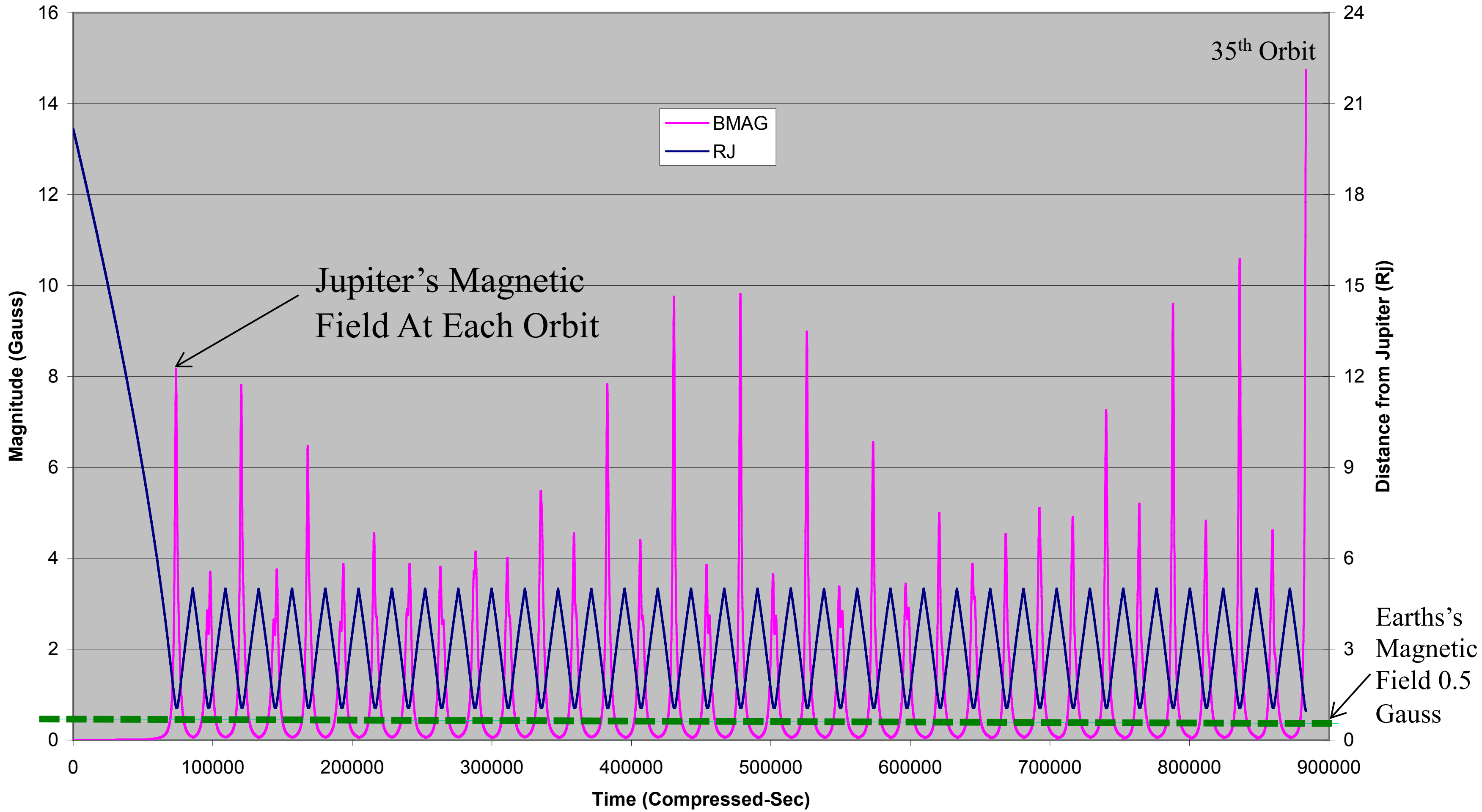


(Courtesy of NASA)

Jupiter's Strong Magnetic Fields

JUNO magnetic field magnitudes in Jupiter's Orbit

Jupiter's magnetic field is on average 14 times larger than of earth!

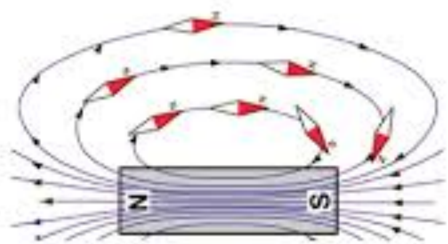


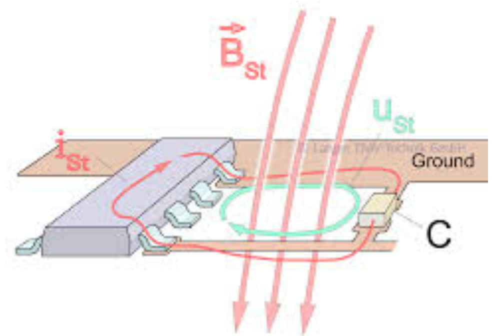
Predicted Model, Actual Fields Are Higher

Magnetic Susceptibility
The Problem Statement

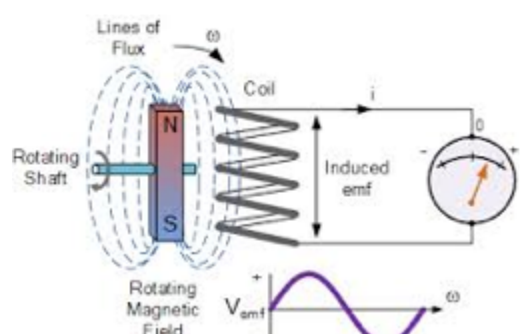
Magnetic Interference From:

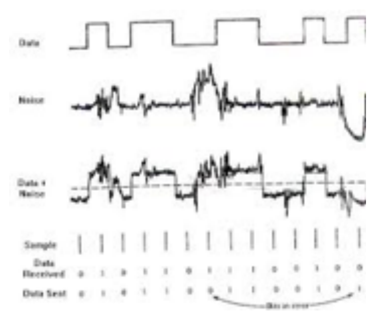
- **Motors**
- **Switching Circuitry**
- **Voice Coils**
- **Scanning Mechanisms**





$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

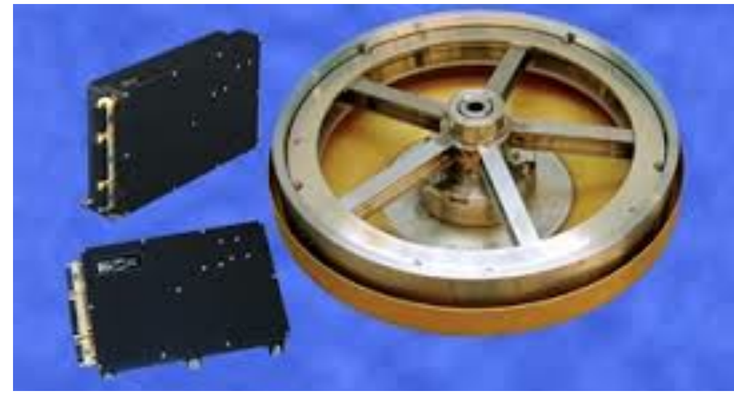


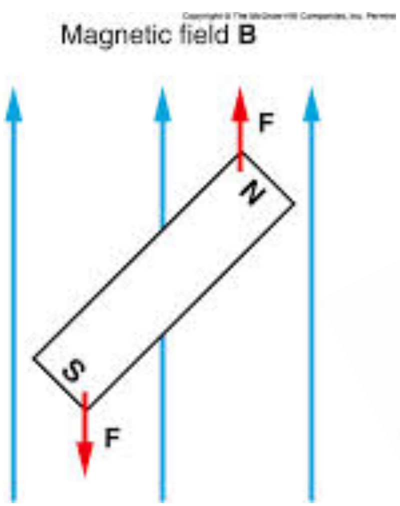


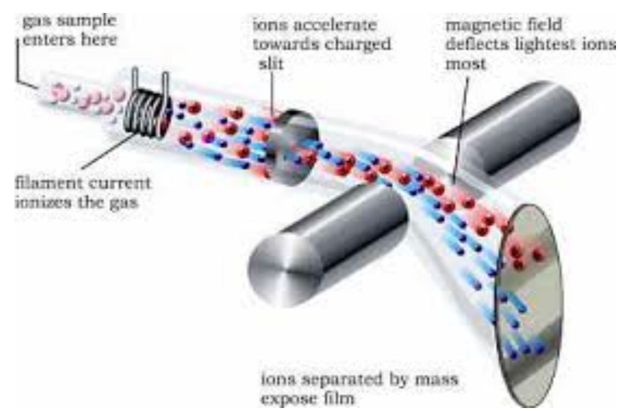
Magnetic Susceptibility
The Problem Statement

Magnetic Interference From:

- Reaction Wheel Assemblies
- Magnetic Torque Bars
- Spectrometers
- RF Switches
- Spin Bearing Assemblies







Magnetic Susceptibility
The Problem Statement

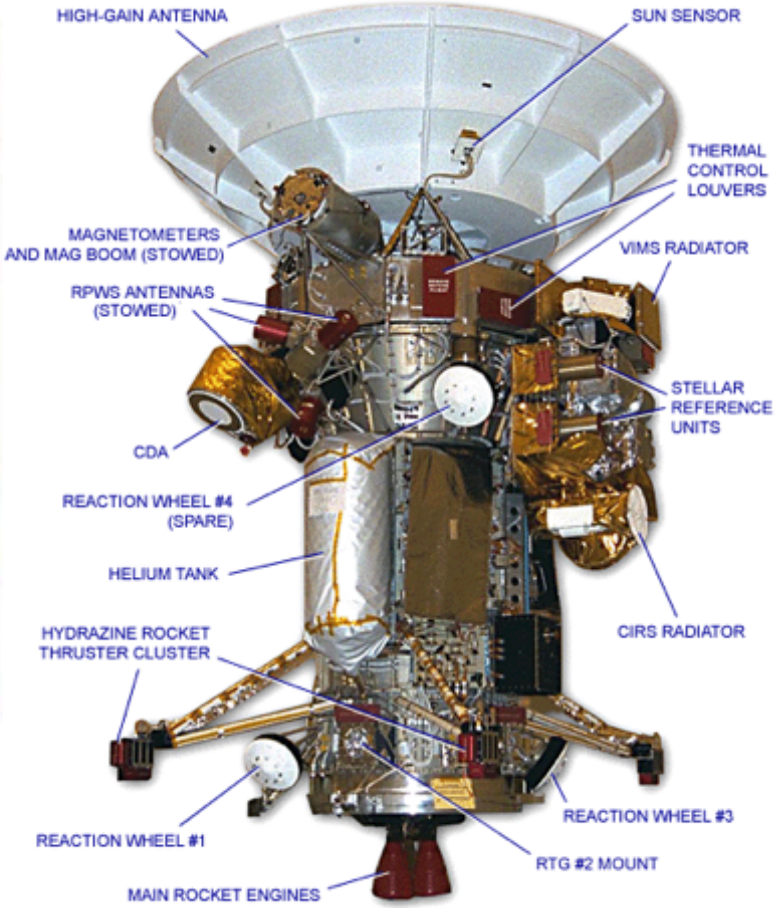
The isolators are in the front end of the microwave radiometer (MWR) science instrument. It is influenced by external magnetic fields. Jupiter's field, when seen from the rotation frame of the spacecraft, will cause cyclic variations in the gain and offset of the system. If uncorrected there would be a direct impact on the antenna temperature retrieval and limb darkening error.

MWR Has Six Radiometers Each With An Isolator, Thus Producing Six Magnetic Interference Concerns

(Isolators Identified As R1 R2, R3, R4, R5, R6)

Magnetic Susceptibility
The Problem Statement

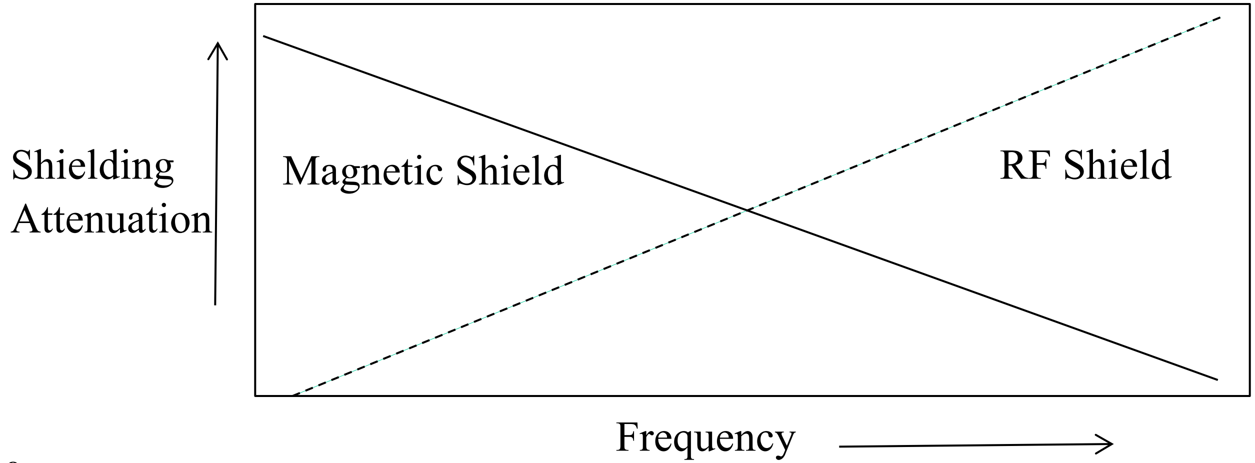
Cassini's Biggest Magnetic Interference From:
Reaction Wheel Assemblies



Cassini Spacecraft (Courtesy of NASA)

RF vs Magnetic Shielding

- RF shielding is required when it is necessary to shield against high frequency interfering sources, typically in the 100 kHz range and above.
- The RF shields are typically copper, aluminum, conductive cloth material, titanium etc.
- These materials work at high frequency by means of their high conductivity and require little or no magnetic permeability.
- Magnetic shields use their high permeability to attract magnetic fields and divert the magnetic energy within the walls of the magnetic shield.
- To protect the MWR, magnetic shielding was necessary and a requirement for mission success

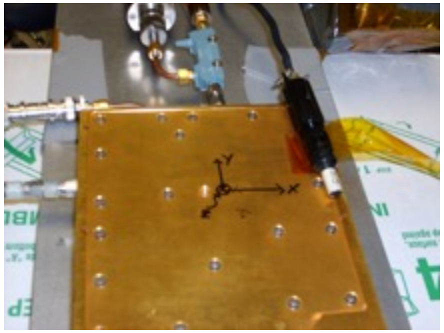


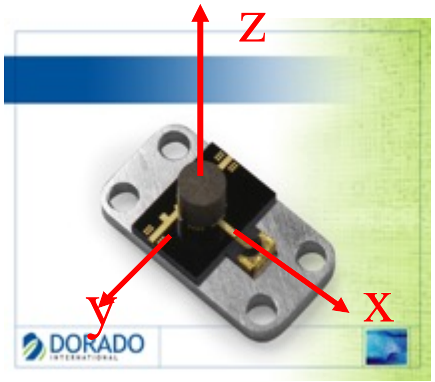
Magnetic Issues and Mitigations

- Exposure of MWR R2 radiometer to 16 Gauss magnetic field showed the radiometer system is
  - Sensitive to magnetic field vector when oriented in a plane perpendicular to the radiometer chain
  - The system gain and receiver noise temperature, and the other key radiometer parameters were changed with applied external magnetic field
  - The nearby isolators were impacted
    - Several tests were performed using magnetic shielding applied to the isolators. No significant improvement
    - Applied magnetic shielding over the whole radiometer chassis whereby two 20 mil thick shields were wrapped around the area of concern. This approach was successful in attenuating the external fields to the point of minimizing its impact on the isolators.
  - Conclusion- a total of **~2 kg of shielding material** is needed to reduces the field at the MWR with the radiometer isolator locations to an acceptable level.
    - Mass was a significant issue in this mission

Efforts to map the constraint space

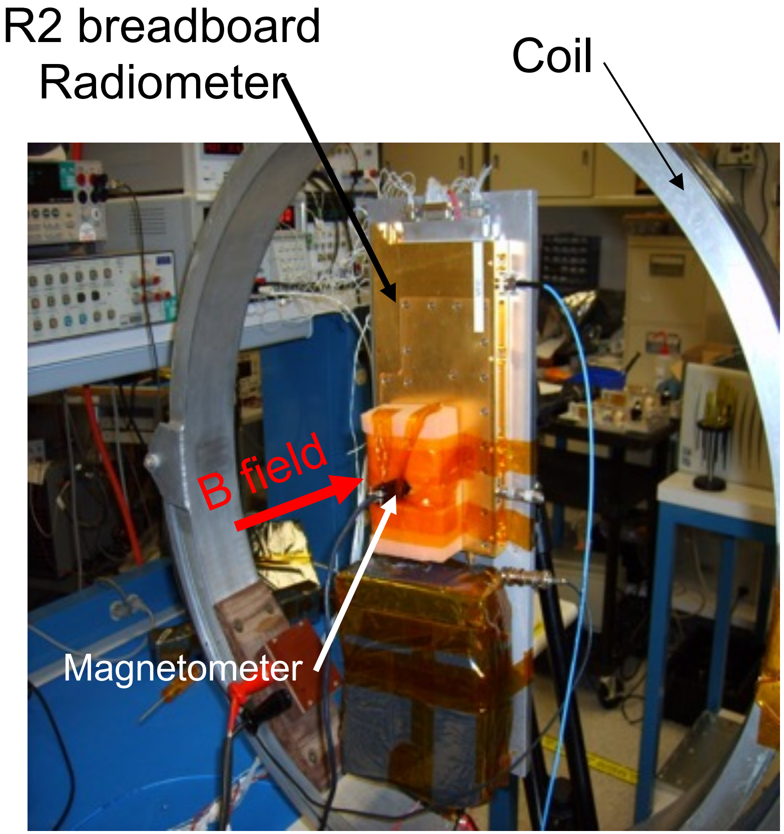
MWR Tested In Three Axes





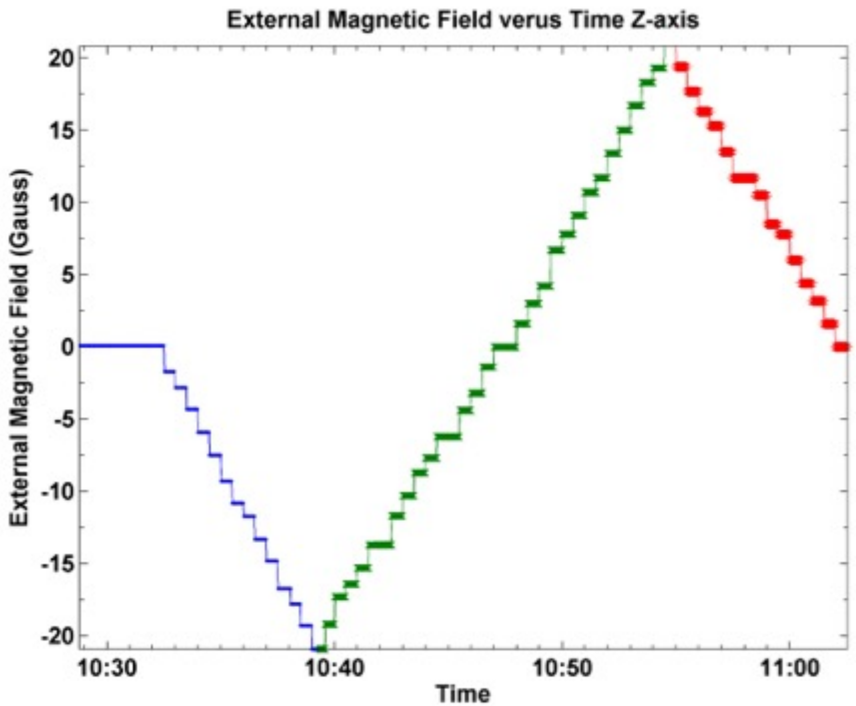
- Defined coordinate system with isolator at the origin
- X& Y axis – B field is in the plane of the radiometer
- Z-axis – B field is perpendicular to the radiometer
- Tested S-parameters on an R4 isolator in the presence of a magnetic material to determine guidelines for minimum spacing between shielding and isolator
- Tested R4 isolator S-parameters in Helmholtz coil in all three axis
  - Test with no magnetic shielding to baseline performance
  - Tested with a magnetic shield around the entire R4 isolator test housing as a proof of concept
- Simulated a magnetic shield package around an individual isolator to determine material saturation and external field attenuation

MWR Magnetic Susceptibility Tests



Magnetic field in z-axis
Test setup

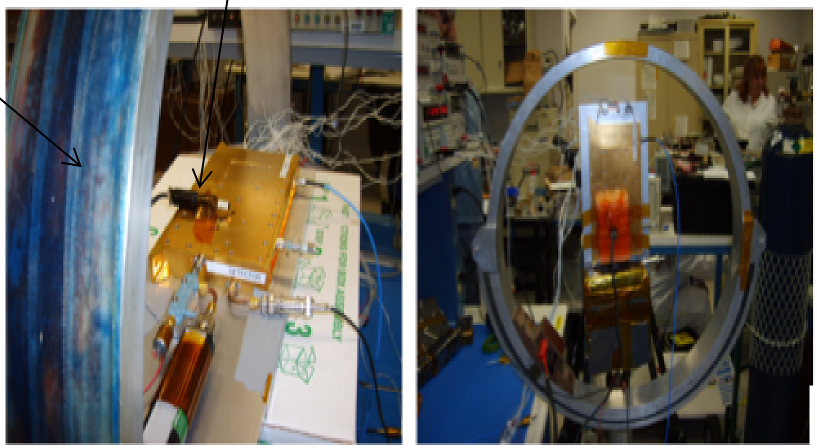
- Radiometer and directional Gauss meter mounted inside a coil.
- Current in coil stepped to vary magnetic field at center of coil (isolator location) from 0 Gauss to -20 Gauss to +20 Gauss then back to 0 Gauss



MWR Magnetic Susceptibility Tests

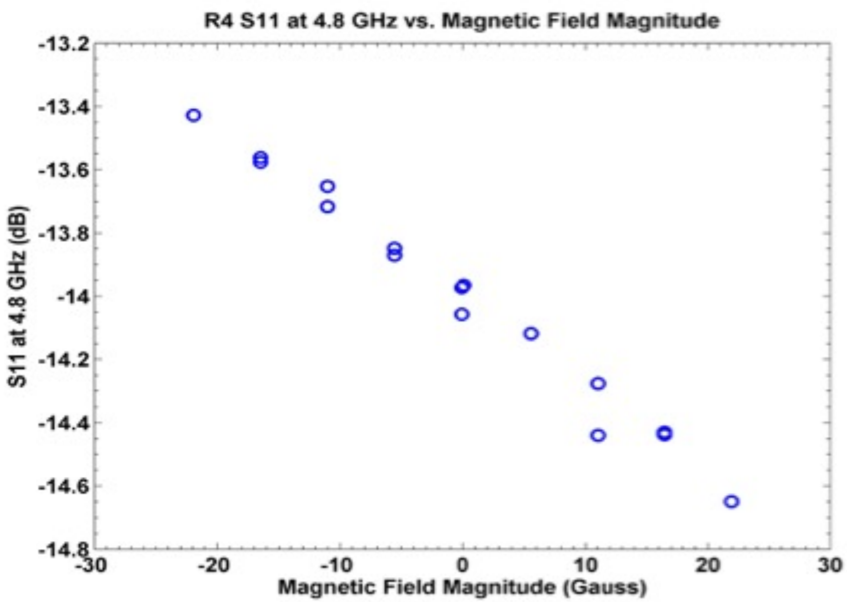
R2 breadboard Radiometer

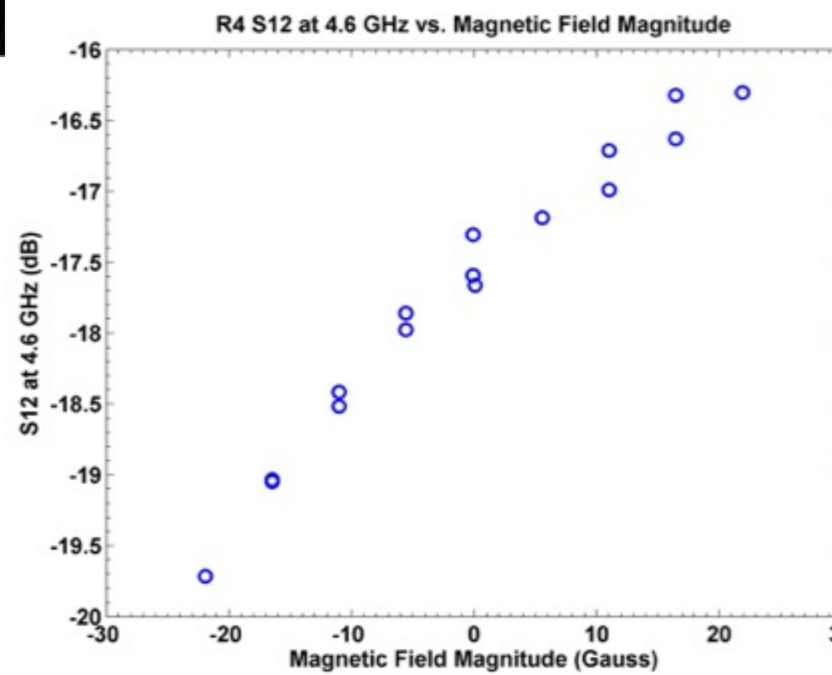
Coil



MWR Tested In Three Axes

- S11 changes by as much as 1.4 dB
- S12 changes by as much as 4 dB
- Change in system gain mainly due to change in S11 (85%) and less from S21 (15%)
- R4 isolator would see a 0.03%/gauss gain modulation, similar to R2 result





Mitigation Approaches

- **Shield entire box**
  - Looks effective from modeling and shielding vendor recommendation
  - No receiver package impact
  - Too much work for the packaging folks, expensive and too heavy
- **Package individual isolators**
  - Needs isolator level pass criterion
  - Impact packaging in very compact board layout
- **Break receivers into two boxes and shield smaller front-end part**
  - Package impact (long time to layout and causes more test effort)
- **Use no isolator**
  - No package impact
  - Carries much more complicated characterization scheme
  - Custom Low Noise Amplifier design
- **Characterize magnetic field impact and calibrate out using data from the magnetometer**
  - No package impact
  - More characterization
  - Could have interference from spacecraft

Mitigation Approaches– cont.

- **Individual Isolator Package Constraints**
  - Magnetic shield will influence RF performance of the isolator if it is too close
  - Isolator magnets may saturate the the magnetic material, reducing its ability to shield against the external field
  - A magnetic shield that provides (X) amount of attenuation will lower the impact of the errors to an acceptable amount
- **Shielding Approach/ Solutions**
  - Shield entire MWR stack
  - Break MWR into two packages and shield smaller front end package
  - Shield individual isolators within one MWR package
- **Looked At The Brute Force Approach (Overall Big Shield)**
  - Least impact on Radiometer packaging and design
  - R2 magnetic shielding tests and vendor initial remarks indicate a need for ~40 mils of magnetic shielding (~2kg)
  - Initial FEM simulations indicate that 40 mils of mu-metal is needed
- **Will meet the 0.01 % gain goal (based on R2 data)**

Isolator Magnetic Shielding Attenuation For Successful Mission

ISOLATORS R1 THROUGH R6

	R1	R2	R3	R4	R5	R6
R error due to magnetic field variations	0.02	0.02	0.02	0.02	0.02	0.03
Required Gain Stability (/)	2.94E-04	7.31E-04	9.85E-04	2.64E-04	1.46E-04	1.26E-04
Required Toffset Stability (K)	0.069	0.043	0.031	0.024	0.019	0.021

Worst Case %Gain/gauss	0.053	0.062	0.07	0.07	0.07	0.07
Worst Case Toffset/gauss	0.021	0.033	0.04	0.04	0.04	0.04

NOTE R3-R6 worst case numbers are WAGs

gauss allowed for Gain requirement	0.55	1.18	1.41	0.38	0.21	0.18
gauss allowed for Toffset requirement	3.27	1.30	0.77	0.59	0.46	0.52

Needed Atneuation against a16G field	0.03	0.07	0.09	0.02	0.01	0.01
	0.20	0.08	0.05	0.04	0.03	0.03

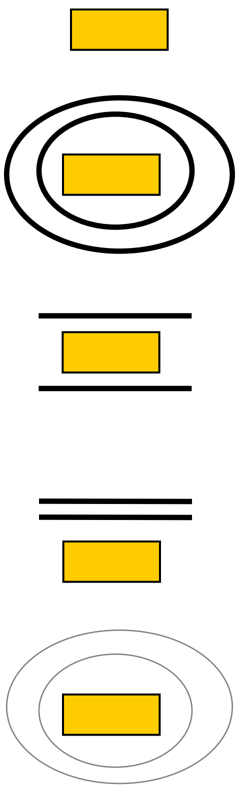
Attenuation (dB)	-29.20	-22.65	-21.12	-32.56	-37.67	-38.99
	-13.78	-21.79	-26.36	-28.69	-30.75	-29.78

NEED AT MOST 40 dB ATTENUATION

MWR Tested In Three Axes

- R2 radiometer was tested with various types of shielding – subset of results shown here for z-axis test [R (%/gauss)]

Error in R (z-axis) [%/gauss]	R1	R2	R3	R4	R5	R6
Baseline worst case	**0.11**	**0.16**	**0.20**	**0.25**	**0.31**	**0.40**
2 sheets connected mu-metal	0.0064	0.0085	0.011	0.013	0.015	0.020
1-sheet mu-metal sandwich, unconnected	**0.089**	**0.12**	**0.15**	**0.18**	**0.22**	**0.27**
2-sheets on top of isolator	**0.08**	**0.11**	**0.13**	**0.16**	**0.19**	**0.24**
2 sheets met glass, wrapped around radiometer	**0.078**	**0.11**	**0.13**	**0.16**	**0.20**	**0.25**



Magnetic Shielding Definitions

- **In order to define specific requirements and design the appropriate shielding strategy, it is helpful to understand some key concepts and terms. These definitions are common in the industry and will provide a valuable foundation for people looking to develop a deeper knowledge and understanding of magnetic shielding theory.**
- **Magnetic Field Strength (H)**
  - Magnetic Field Strength (H) describes the intensity of a magnetic field in free space. Field strength (H) is measured in Oersteds (Oe) and is a function of the intensity of the magnetic source and the distance from the source at which it is measured.
- **Magnetic Flux Density (B)**
  - Magnetic Flux Density (B) describes the concentration of magnetic lines within a material. Flux density (B) measured in Gauss (G), describes the number of magnetic lines that exist in a given cross sectional area of a material. Flux density depends on the intensity of a magnetic source, the distance of the material from the magnetic source, and the material's permeability, or attractiveness to the magnetic field.
- **Magnetic Permeability (μ)**
  - Magnetic Permeability (μ) refers to a material's ability to attract and absorb magnetic lines of flux. Materials with a strong attraction for magnetic fields generally have a high permeability. Mathematically, permeability $\mu = B/H$, which states that the permeability of a material can be determined by taking the ratio of the measured flux density (B) in the material at some point in space to the magnetic field strength (H) at the same point in space. Magnetic shielding materials are typically chosen for their unusually high permeabilities.

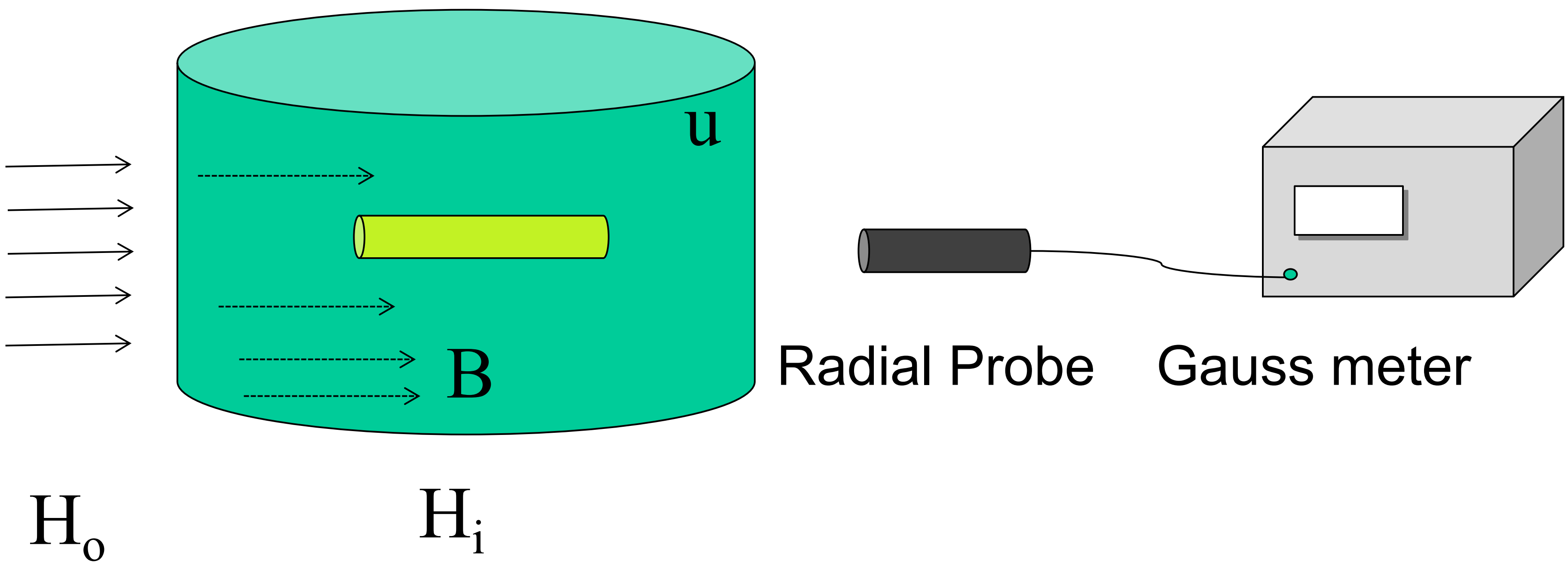
Magnetic Shielding Definitions

- **Saturation**
  - Saturation refers to a material's limiting point for absorbing additional lines of magnetic flux within a given cross sectional area. Each permeable material has a specific saturation point. Once a shielding material becomes saturated, it will no longer attract lines of flux and will no longer function as expected. (Note: saturation and permeability characteristics of a material are inversely related: the higher a material's permeability, the lower its saturation point.)
- **Attenuation**
  - Attenuation is a ratio for measuring the effectiveness of a given shield and often defines the shielding objective. The ratio is expressed in field strength (H_1) at a given point versus the resulting field strength (H_2) at the same location with the introduction of the magnetic shield. For example, a shield that provides a field reduction of 100 times has an attenuation of 100:1.

$$\text{Attenuation (dB)} = 20 \text{ x } \log_{10} (H_1/H_2) = 20 (\log 100/1) = 40 \text{ dB}$$

Basic Measurements Of Attenuation

Magnetic Shielding Material
With Source or Victim Inside

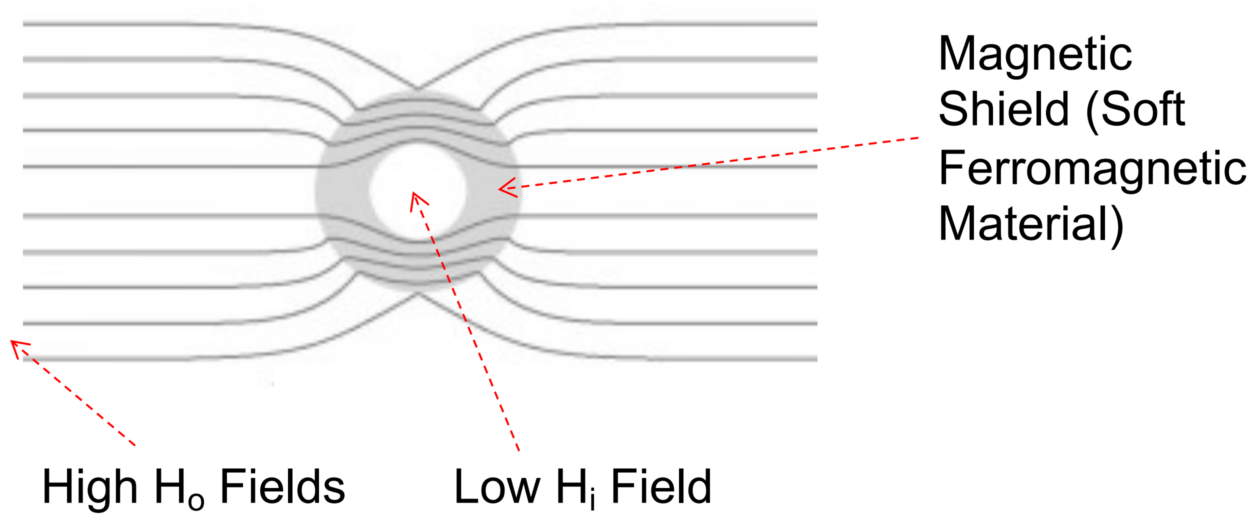


Magnetic Field Without Shield = H_o

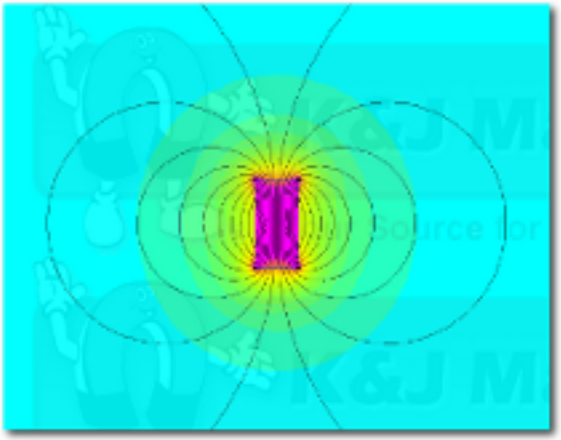
Magnetic Field With Shield = H_i

How Magnetic Shields Perform

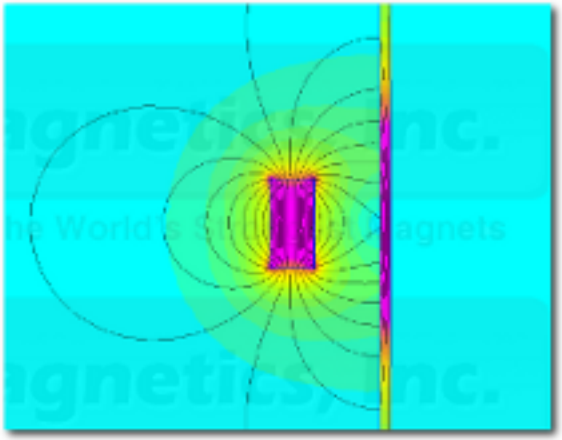
- Magnetic shields re-direct magnetic flux around it so that it reduces the magnetic field inside the shield, thus protecting the victim inside the shield
- Magnetic shields do not reflect, destroy or permanently absorb magnetic fields, but rather provides a low reluctance path for the magnetic fields to follow.
- The type of material that can provide the lowest reluctance path for magnetic fields should be able to attract these flux lines, such as ferromagnetic material
- Ferromagnetic materials are necessary because shields work by pulling the magnetic fields towards them and away from what is being shielded
  - The magnetic field will be concentrated within the shield itself



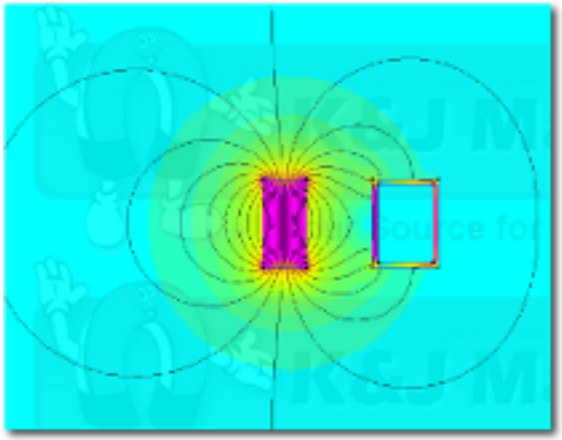
How Magnetic Shields Perform



mA Magnet In Free Space



A Steel Wall



A Steel Enclosure

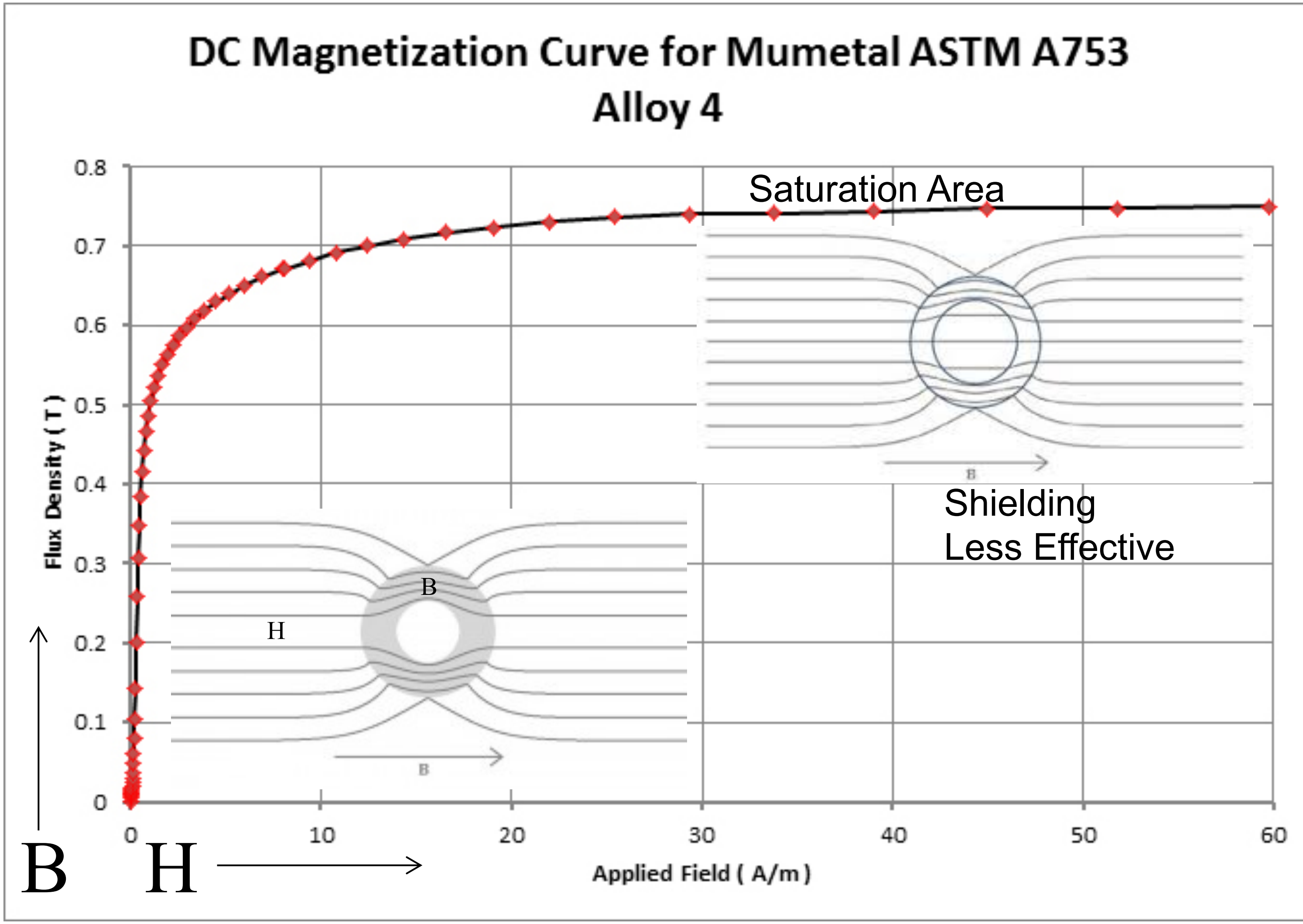
First, one important point must be clear: Magnetic shielding does not block a magnetic field. No material can stop the lines of flux from traveling from a magnet's North pole to it's South pole. The field can, however, be redirected.

How Magnetic Shields Perform

$B=\mu H$

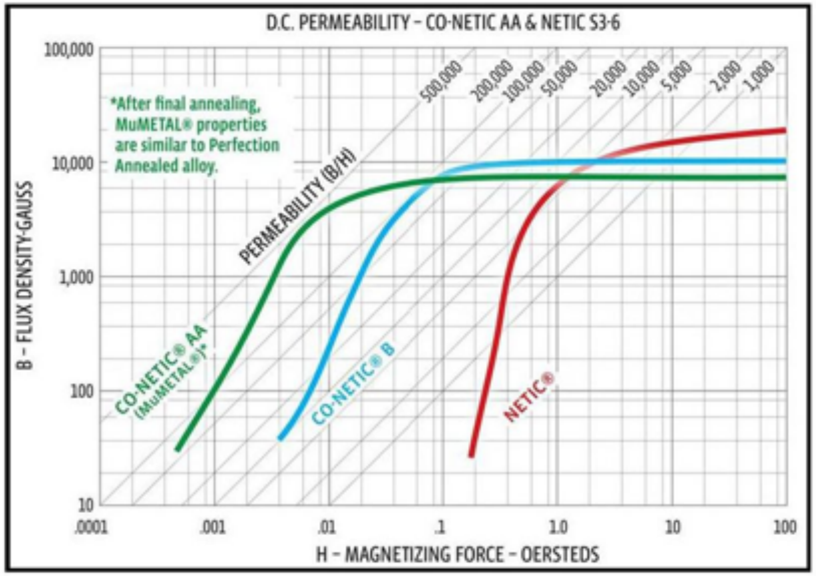
$B/H=\mu$

μ is measured of properties that allow a material to absorb a magnetic field.



How Magnetic Shields Perform

- Magnetic shields are dependent on the permeability of the material.
- The ratio of magnetic flux in Gauss to magnetic field in Oersteds in a material is defined as permeability Mu, **μ**, which is the measure of the properties that allow a material to absorb a magnetic field.
- The ratio is high for ferromagnetic materials, which can go as high a 100,000.
- The permeability in air is 1, so the Gauss and Oersteds are numerically identical.
- Some confusion with units can arise, so the International System of Units uses the metric system and replaces Gauss and Oersteds with Tesla and Ampere-turns per meter (A/m).



How Magnetic Shields Perform

- Magnetic shields are dependent on the strength of the magnetic field it is in.
- The shield conducts the magnetic field through the material. The more material in the shield, the more effective it becomes.

$$B = (1.25 * D * H_o)/t$$

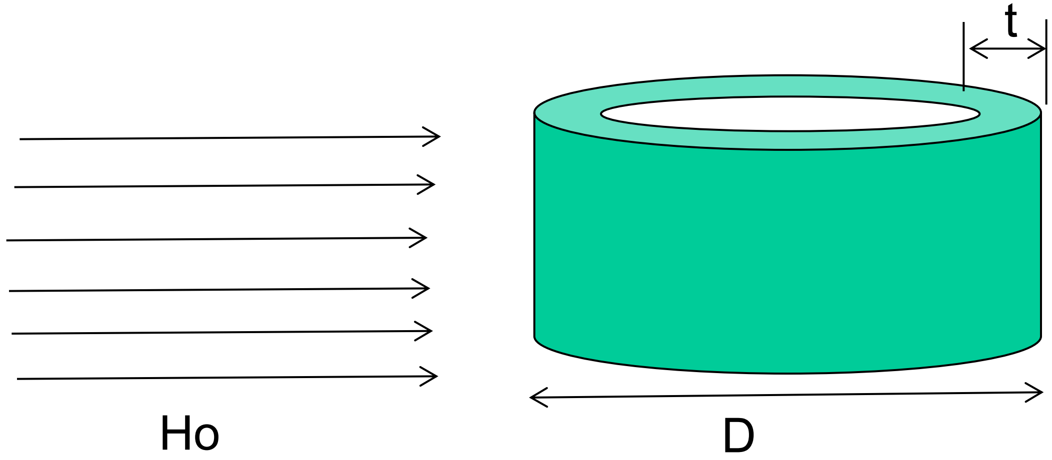
Where:

B = flux density in the shielding material in Gauss

D = Diameter or diagonal of the shield in inches

H_o = Ambient transverse magnetic field

t = Thickness of the shield in inches

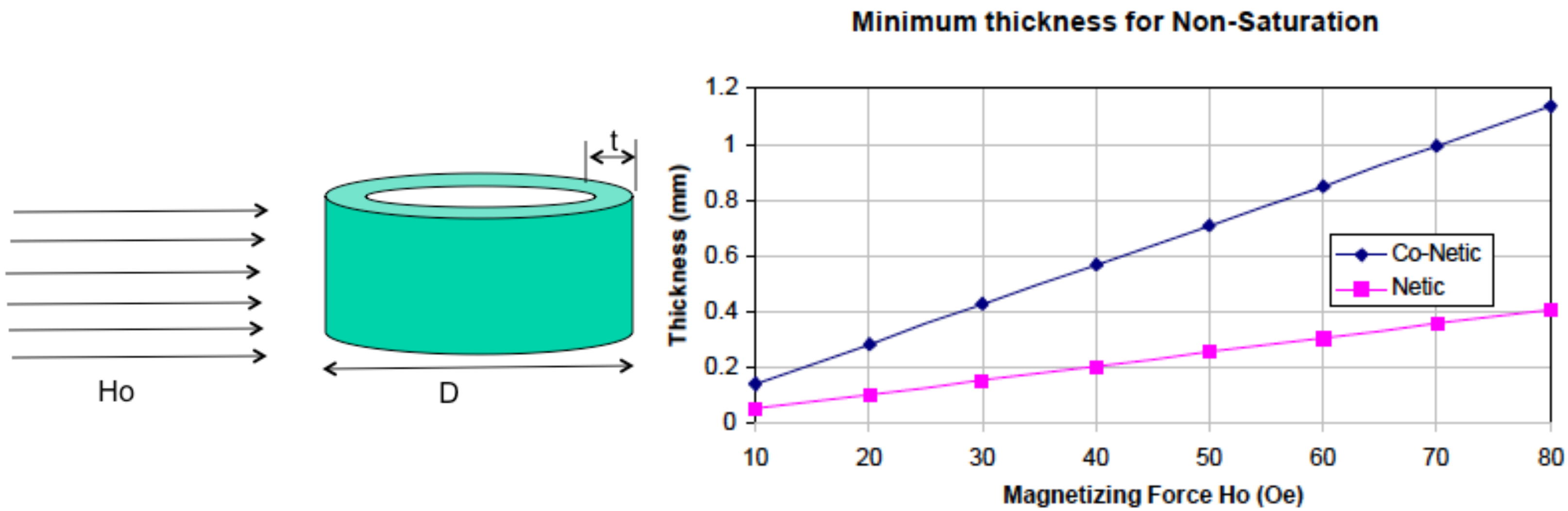


How Magnetic Shields Perform

- Saturation of a magnetic shield depends on the ambient or external field Ho, geometry and thickness of the material.
- For a cylinder (or tube) with inner diameter of D, in a field of Ho, the minimum necessary thickness "t_{min}" is given by:

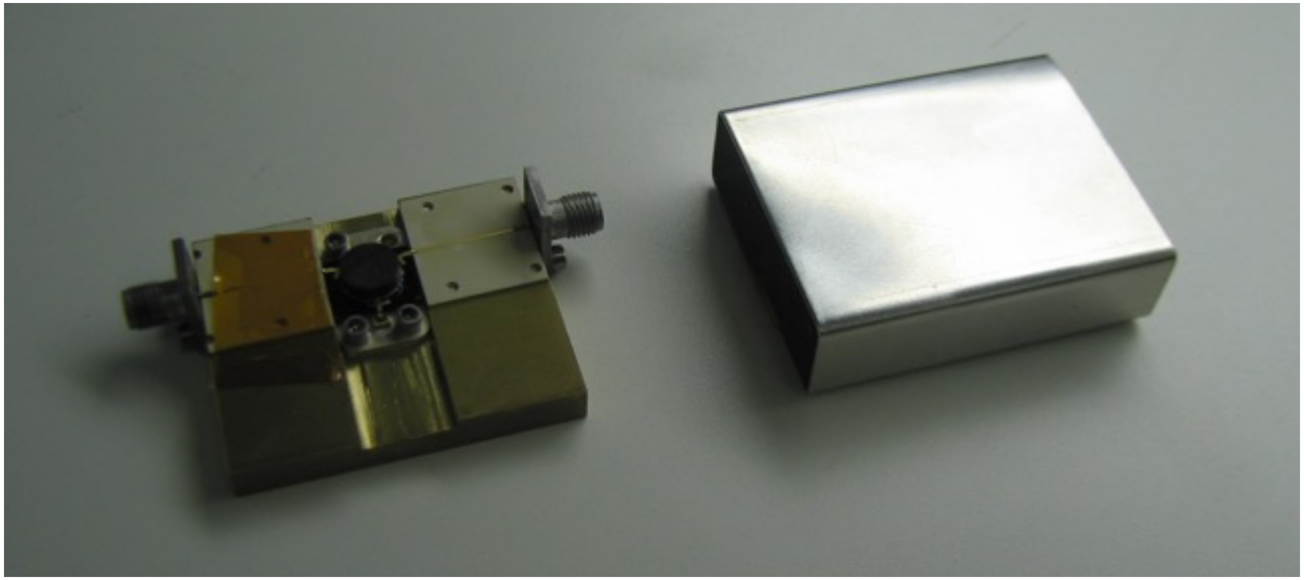
$$t_{min} = (1.25*D*H_o)/B_{max}$$

Where B_{max} is 7500 Gauss for CoNetic alloy, the t_{min} for different ambient field strengths is shown in the following plot:



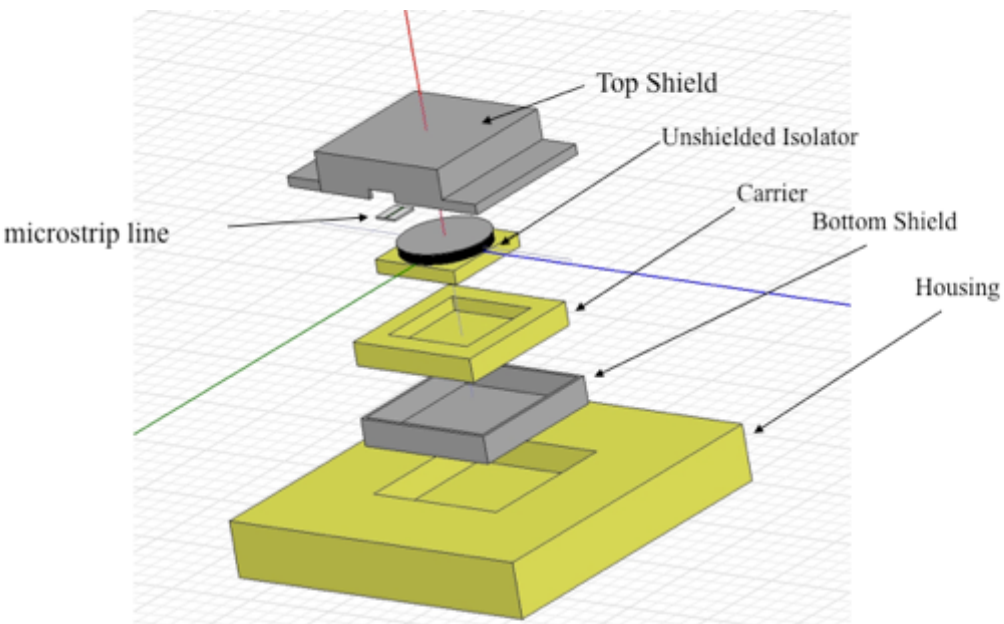
How Magnetic Shields Perform

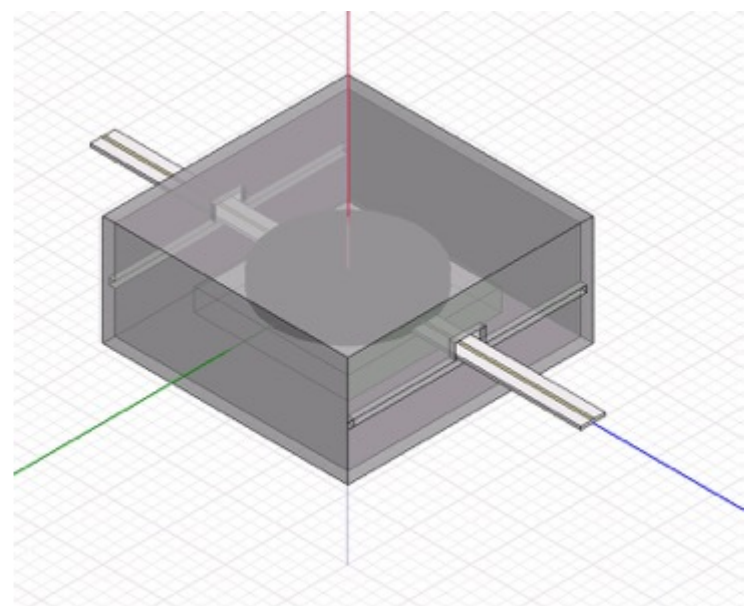
- There are many factors to consider in a shield design
  - Appropriate shielding material/alloy must be selected
  - Right shielding thickness for the needed attenuation
  - Most effective shape (round, square etc)
  - Size, penetrations for inputs/outputs
  - Location of the shield relative to the source



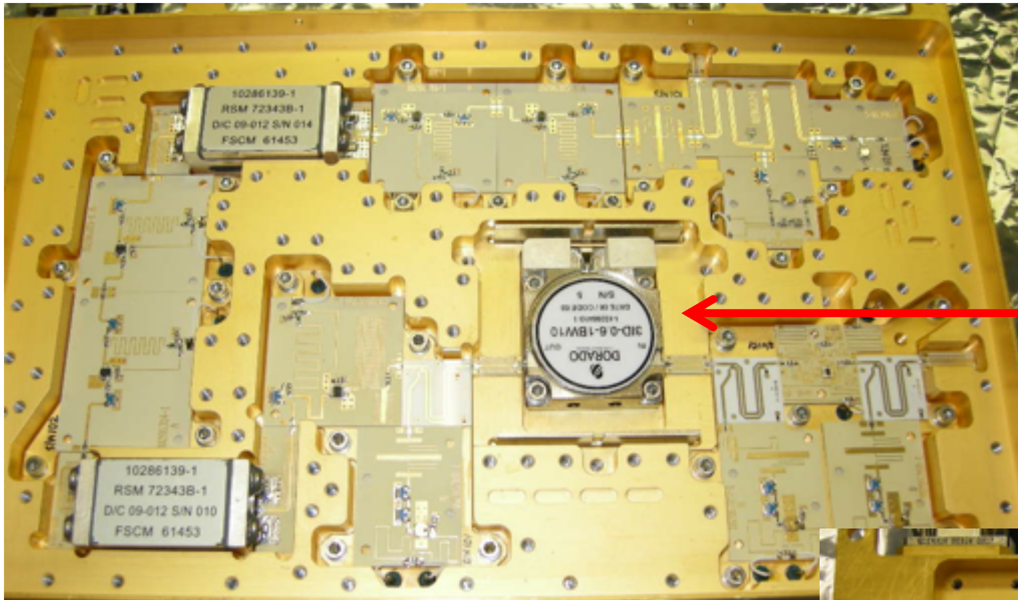
Shield Source or Victim

- Should the source of interference or the sensitive device be shielded
  - It depends on several factors
  - Shielding the source such as a permanent magnet or strong motor may involve stronger fields and thus thicker shields
  - One must be sure that all interference sources are shielded or the most sensitive device will still be affected
  - Size, penetrations for inputs/outputs
  - Location of the shield relative to the source

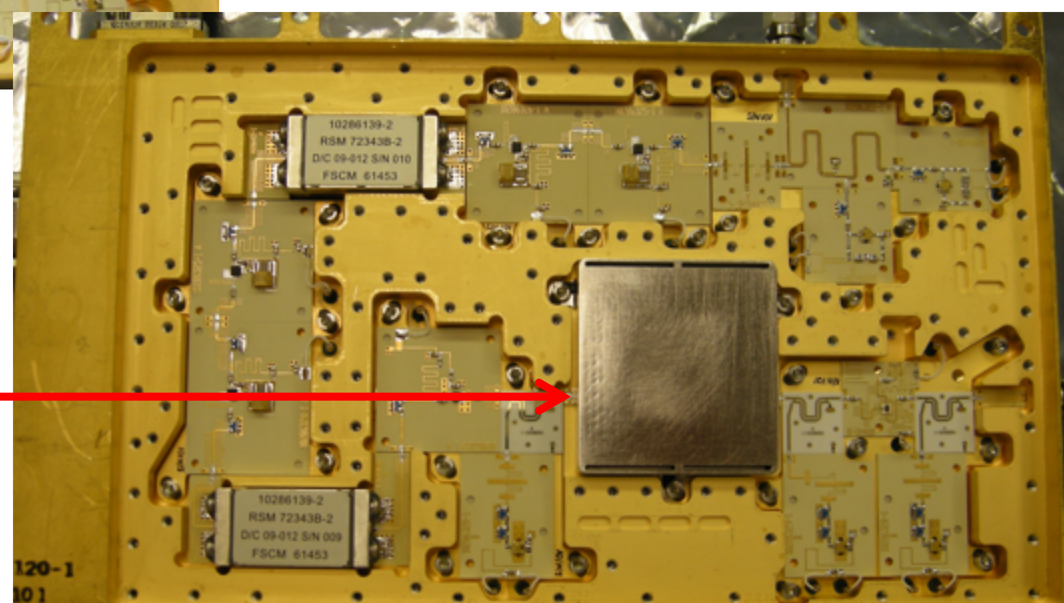




MWR Flight Mag Shield Design



Isolator Unshielded



Isolator Shielded

Magnetic Shielding Rule Of Thumb

- Permeability is the degree of magnetization of a material that responds linearly to an applied magnetic field. Permeability is a measure of a material's ability to absorb magnetic flux. The higher the number, the better the shield.
- Low carbon steels have a Permeability of 1000 - 3000, while MuMetal can have values as high as 300,000 - 400,000.
- The saturation point is the flux density at which the material can not contain any more magnetic flux. Steel saturates around 22,000 Gauss, while MuMetal saturates at about 8,000 Gauss.
- In lower flux density fields, such high permeability materials provide greater attenuation. In higher field densities, MuMetal becomes saturated, and loses its effectiveness. In these cases, steel provides good attenuation and a much higher saturation threshold.
- **Which material is right for you depends on your specific shielding problem. For low field strength, sensitive electronics, MuMetal can provide better shielding than steel. For many applications involving large, powerful neodymium magnets, the higher saturation point of steel serves better. In many specific cases, a steel sheet-metal shield is often the best solution.**

Magnetic Shielding Design Guides

- **Magnetic shielding theory and its primary shielding formulas are based on the perfect shielding geometries of a sphere or an infinitely long cylinder. As these geometries are typically not practical from a fabrication standpoint, it is important to understand how physical characteristics influence the effectiveness of your shield design.**
- **Geometry**
  – We base most magnetic shielding formulas and principles on the optimal geometry of a sphere or an infinitely long cylinder. As these shapes are not generally practical in the real world, we need to subjectively degrade values for a material's permeability based on the differences between a given shield's geometry when compared with that of a sphere or infinitely long cylinder.
- **Shape**
  – Creating rounded shields such as cylinders or boxes with rounded corners is beneficial because it is difficult for magnetic flux lines to turn 90 degrees. Gentle radii provide a better path for magnetic flux lines than sharp corners. Some percentage of magnetic flux lines that are already entrapped within the skin depth of a material will tend to leave the material whenever they encounter a sharp corner. To contain and redirect flux that is already entrapped, designs should generally include gentle radii. When designing your shield, it is a good idea to keep the shape simple, always envisioning a "path of least resistance" upon which the magnetic flux can travel.

Magnetic Shielding Facts

- **Size**
  - Shield size is a significant factor in its overall performance. All things being equal, smaller shields result in better performance, which means that it should always be your goal to design a shield that will envelop the component or space you are attempting to shield as closely as possible. Additionally, because materials are a major cost component in shield design, smaller shields will yield better performance at a lower cost.
- **Magnetic Continuity**
  - Magnetic continuity is necessary for proper flux diversion and is best achieved by developing single-piece shields free of surface interruptions. When conditions make single-piece shields impossible, we can maintain continuity at corners and transitions either mechanically with good overlapping contact or through welds using parent material. Maintaining continuity between surfaces enhances overall shield design and ensures that the magnetic flux will be able to continue along the lowest reluctance path

Magnetic Shielding Facts

- **Closure**
  - Whenever possible, a shield should be closed on all sides. This configuration, even if rectangular, most closely approximates a sphere and creates a closed "magnetic circuit." Additionally, complete closure provides shielding in all axes thus guaranteeing the highest shield performance. Removable covers, lids, and doors are often required to achieve closure. In these instances, it is critical to ensure continuity through mechanical connections to avoid compromising shield performance.
- **Length to Diameter Ratios and the Impact of Openings**
  - When you are unable to close one or both ends of a shield, or if the shield must have holes, it is important to consider the impact that penetrations will have on the performance of your shield. Generally, magnetic fields can travel into an opening up to five times the diameter of that opening. This means that for shields with open ends, the ratio of the shield's diameter to its length should be increased as much as possible to improve performance. By increasing the length of a shield while maintaining its diameter, we approximate an infinitely long cylinder — a configuration that improves the shielding performance at a region of increasing distance from the opening. Similarly, we can add tubulations around openings to protect shields with large holes and penetrations. The length of the tubulation should be proportionate to the diameter of the opening that it is protecting, coming as close to five times the length of the diameter as possible to avoid a total degradation of the attenuation at that location.

Magnetic Shielding Facts

- The thicker the shield, the more effective
- Multiple layered shields are more effective than single shields
- Nature of the shielding material is important. The higher the permeability, the more effective the shielding attenuation
- Post annealing of fabricated shield is important.
- Shock/mishandling/dropping shielding material will reduce shielding effectiveness
- Rounded corners are more effective than sharp corners
- Spherical shields are ideal over square design
- The larger the volume the more effective the shield
- Item that requires shielding needs to be at the most geometric center of volume.
- Items that require shielding: permanent magnets, hard/soft magnetic materials, ferrites, motors, isolators, actuators or any device sensitive to external magnetic fields or that may act as a source.
- Caution needs to be taken into consideration for low temperature magnetic materials shielding.

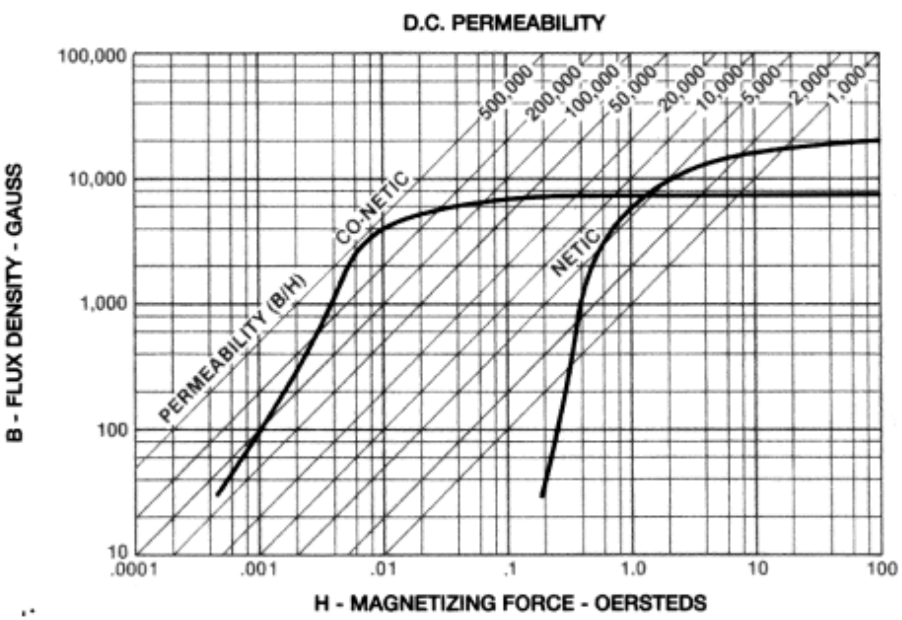
Basic Magnetic Shielding Formulas

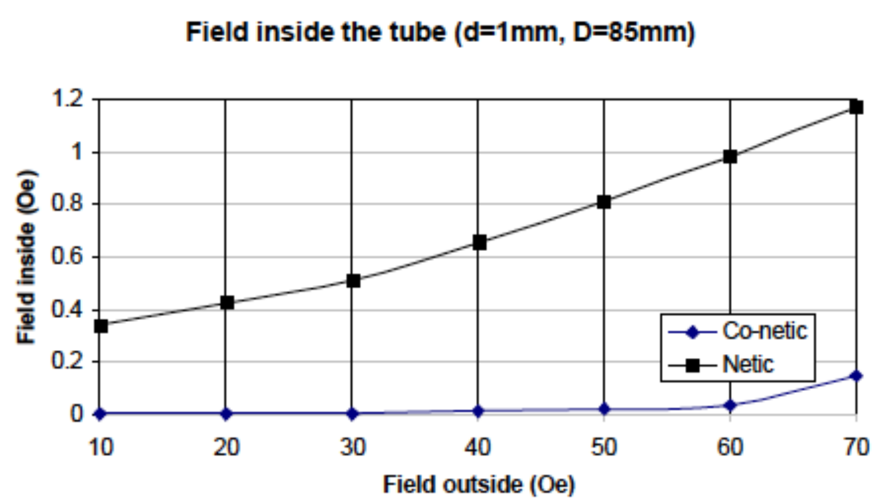
- **SHIELDING CALCULATION FORMULA**
  - Shielding attenuation factor (A) is a ratio of the magnetic field strength outside of the magnetic shield (Ho) and the resultant field on the inside of the shield (Hi) i.e. Ho/Hi (no units) or **A = 20 x log(Ho/Hi) (dB)**
- Shielding formula is based on permeability of the material, shape and size of the shield and the material thickness. In most cases these formulae are only approximate.
- For a closed shielding can :
  - **A = 4/3 x (μ x t/D)** where “Mu” **μ** is relative permeability, t: material thickness, D: shielding diameter
- For a long hollow cylinder in a magnetic transverse field
  - **A = μ x t/D**
- For a cubic shielding
  - **A = 4/5 x (μ x t/a),** where a: box side length.
- For multiple layer shields (zero gauss chambers) with air gaps provided by insulating spacers, the shielding factors of the individual shields are multiplied together resulting in excellent shielding factors.
- For a double layer shield:

  A= A1 x ((A2 x (2 x change in diameter /diameter))

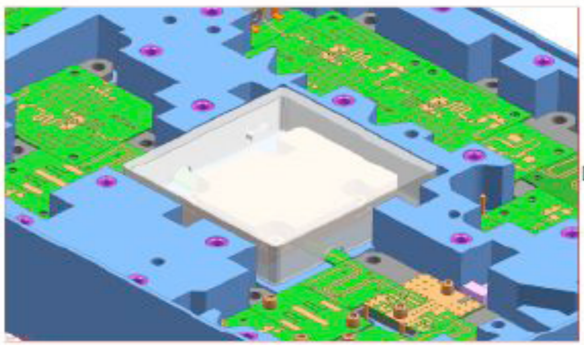
Basic Magnetic Shielding Formulas

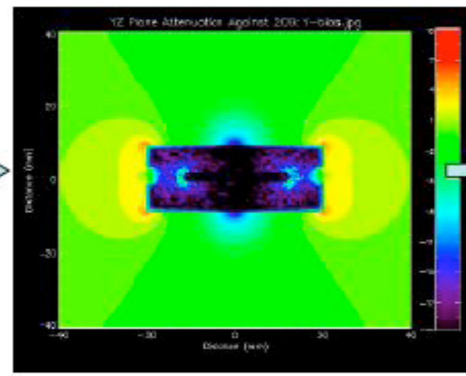
- **Finding Attenuation For A Simple Cylinder Of Conetic Alloy Shield**
  - Shielding attenuation factor (A) of a magnetic shield depends on external magnetic field Ho, thickness t and inner diameter D. To find A, one needs to calculate the magnetic flux density using the formula B = (1.25*D*Ho)/t then find corresponding **μ** permeability using charts. Attenuation A can then be found as A = **μ (**t/D) and the field inside is Hi = Ho/A is a ratio of the magnetic field strength outside of the magnetic shield (Ho) and the resultant field on the inside of the shield (Hi) i.e. Ho/Hi (no units) or **A = 20 x log(Ho/Hi) (dB)**

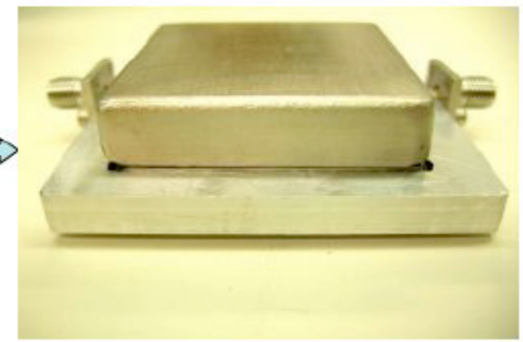




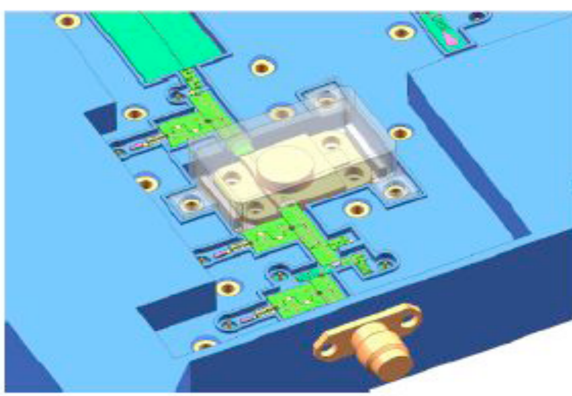
Shielding Experience

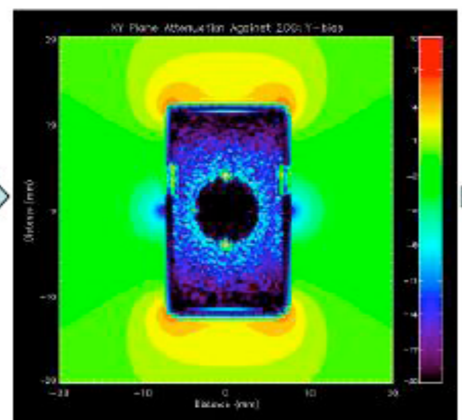


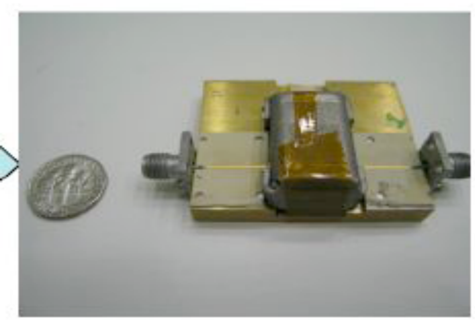




R1 - R3 (above)   R4 - R6 (below)

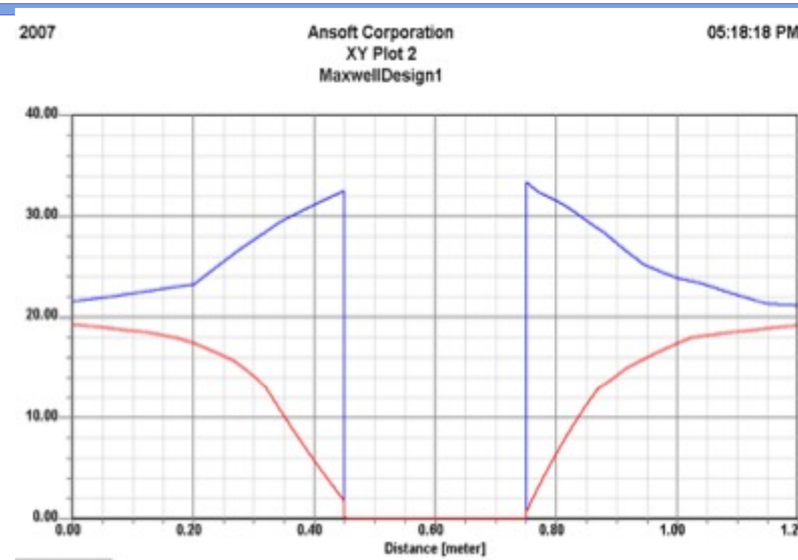


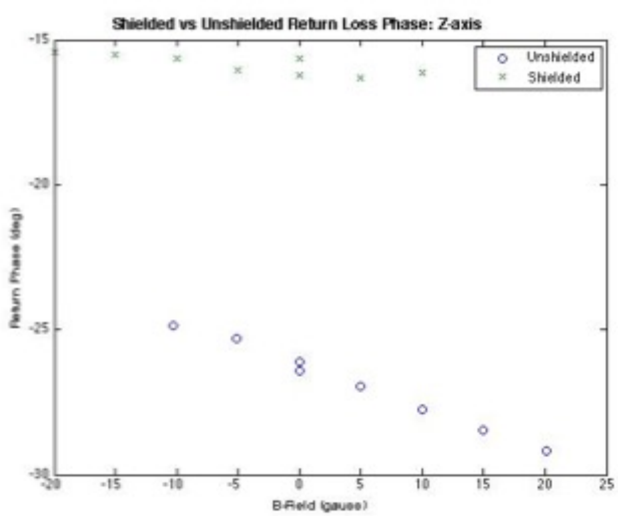


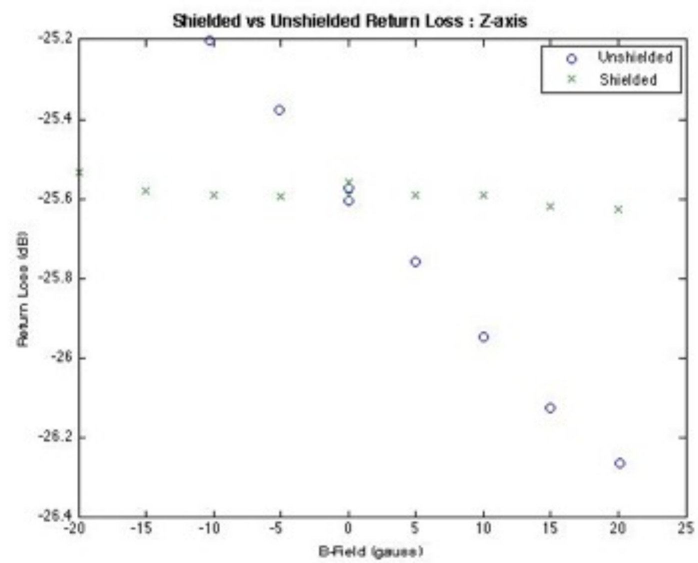


Modeling Approach and Solutions

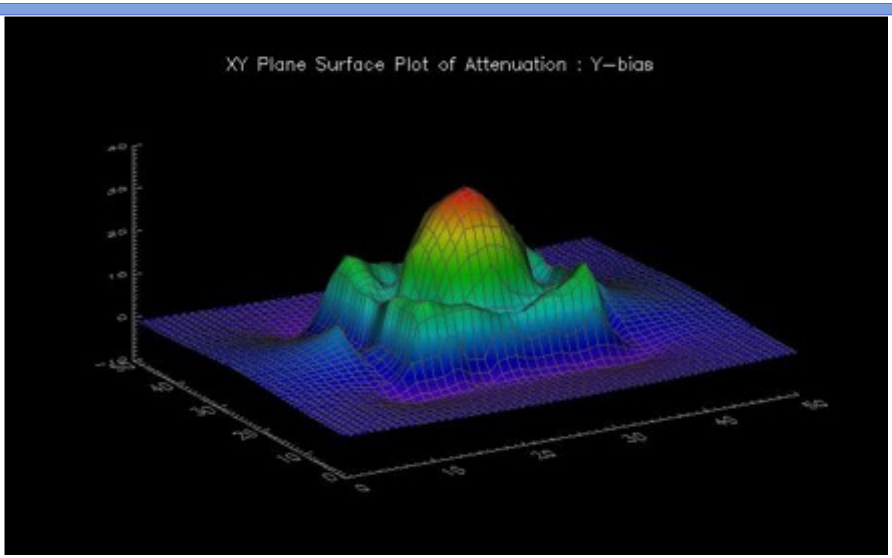
- Model consists of a 30 cm 1 cm thick cube surrounded by 40 mils of mu-metal in a 20 gauss uniform field
  - Used vendor “stock” mu-metal B/H curve
  - Shielding may actually be more effective than indicated due to the fidelity of the simulation
- Experience with using Mu-metal shield from past NASA missions in general: Voyager, Galileo, Cassini
- R4 shielding results are presented

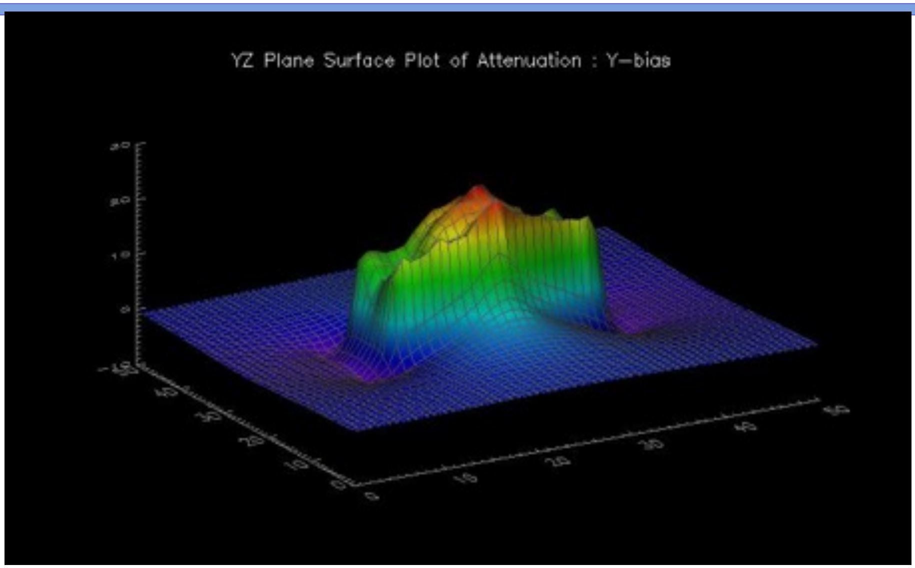


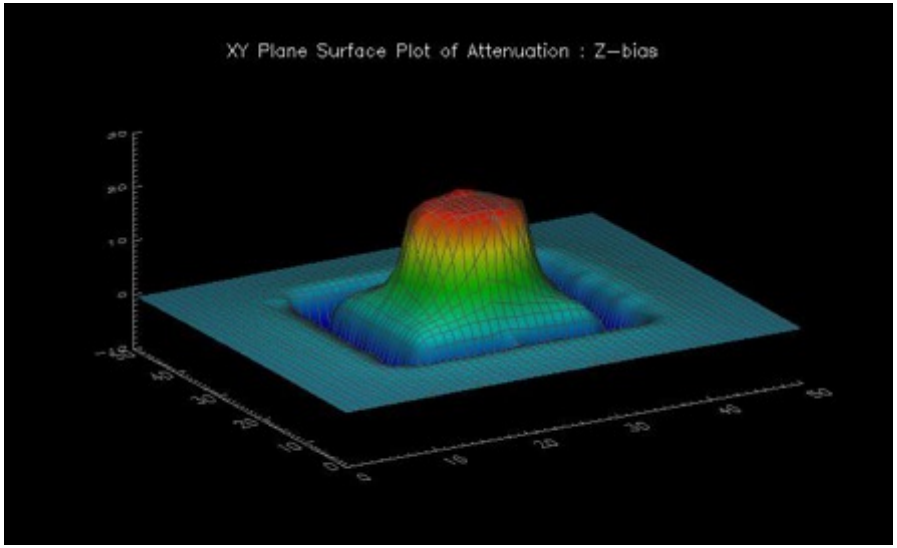


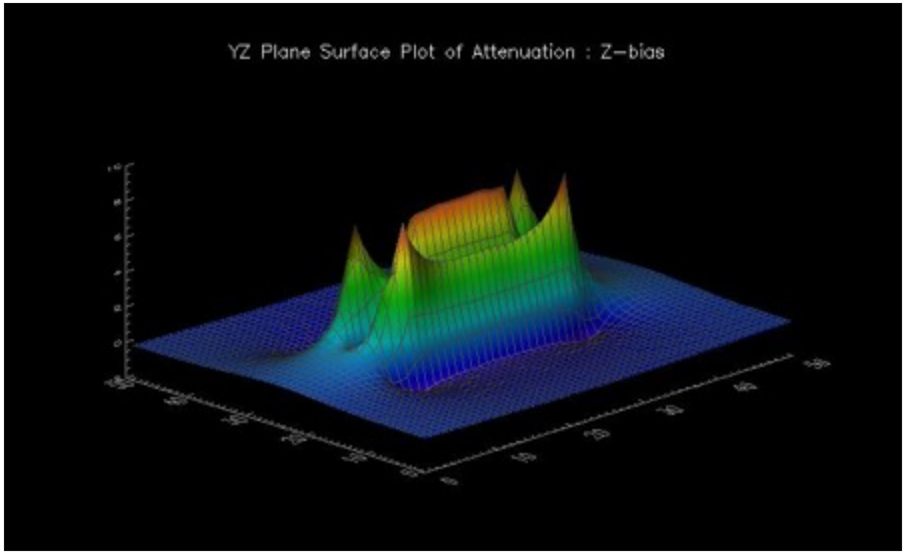


Current R1-R3 Concept Attenuation Surface Plots

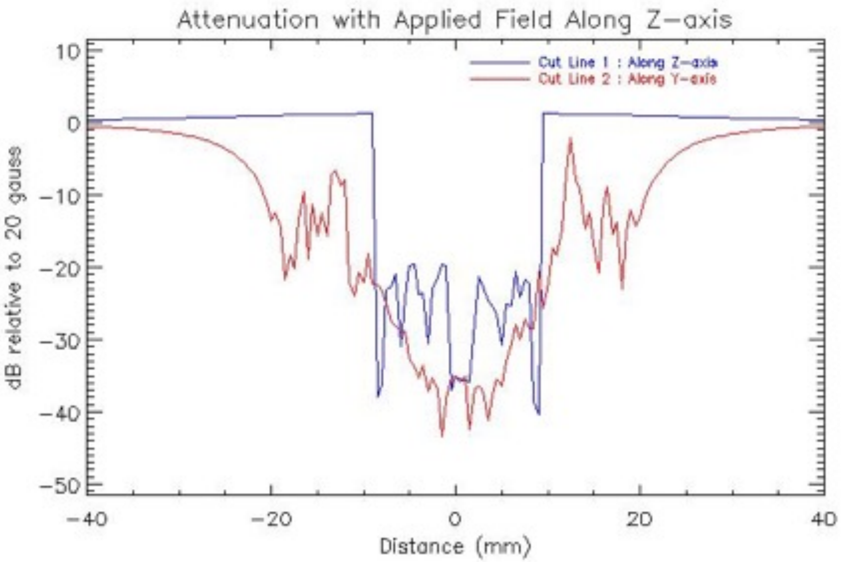


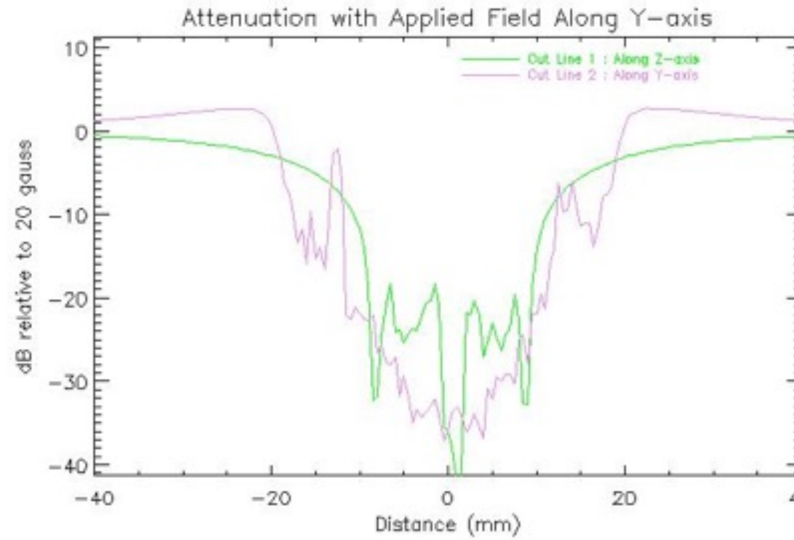


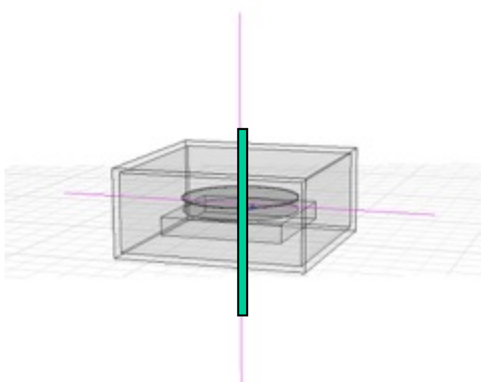


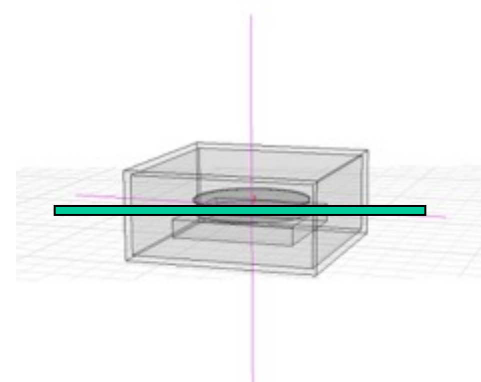


Current R1-R3 Concept Attenuation Surface Plots



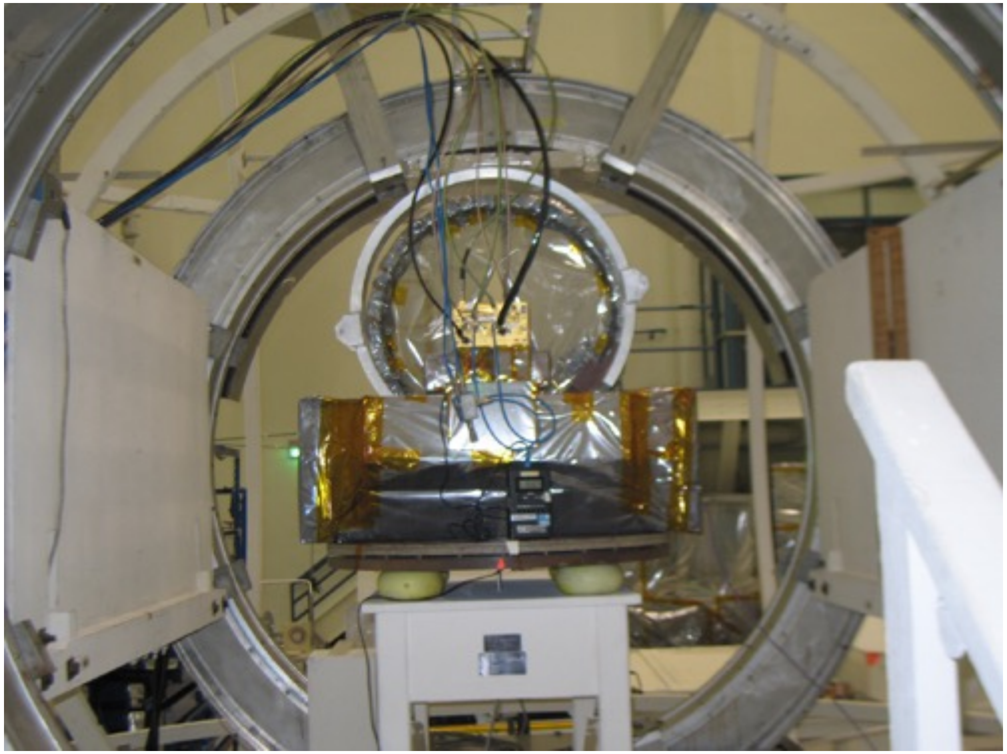






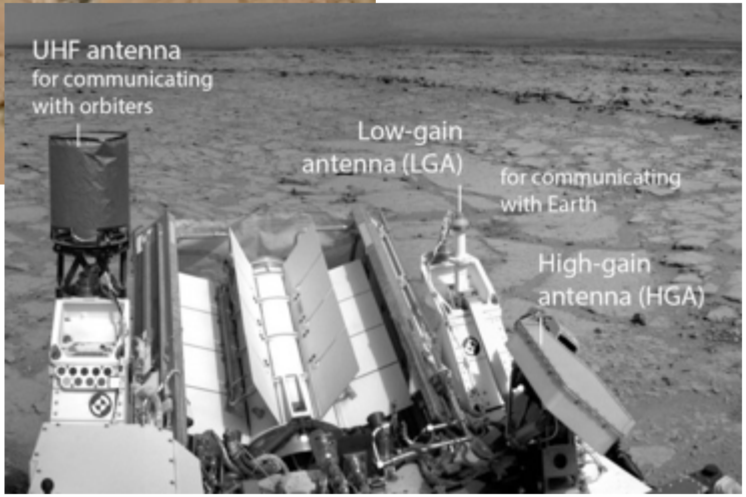
Final Verification Of MWR

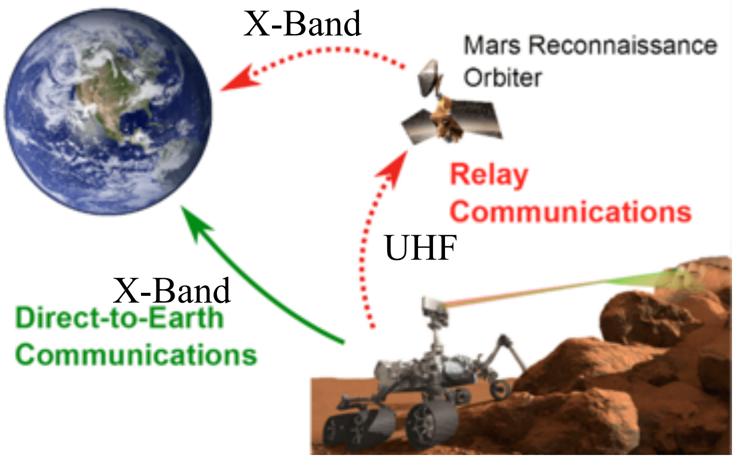
- MWR Flight Unit Placed Inside Helmholtz Coil
- External coils generated uniform fields with a magnitude of 16 Gauss with the field parallel to the coil axis and encompassing all of MWR
- The magnetic field was modulated at 2 rpm (simulates a rotating spacecraft)
- **MWR MET ALL ITS PERFORMANCE CRITERIA**



Radiated Electric Fields
The Problem Statement

Mars Science Laboratory
Uses Two Tx/Rx To
Communicate With Earth
Receivers Operate At
X-Band at 7.14 GHz
And
UHF at 437 MHz

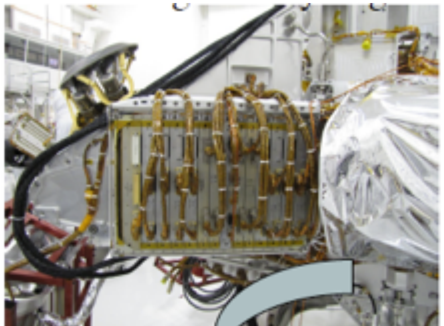


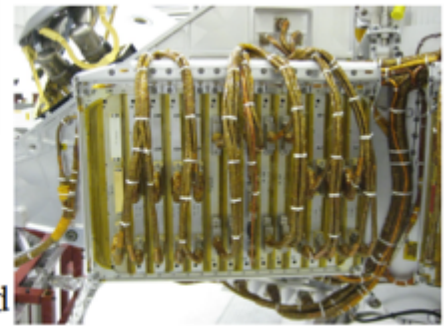


Radiated Emissions Example

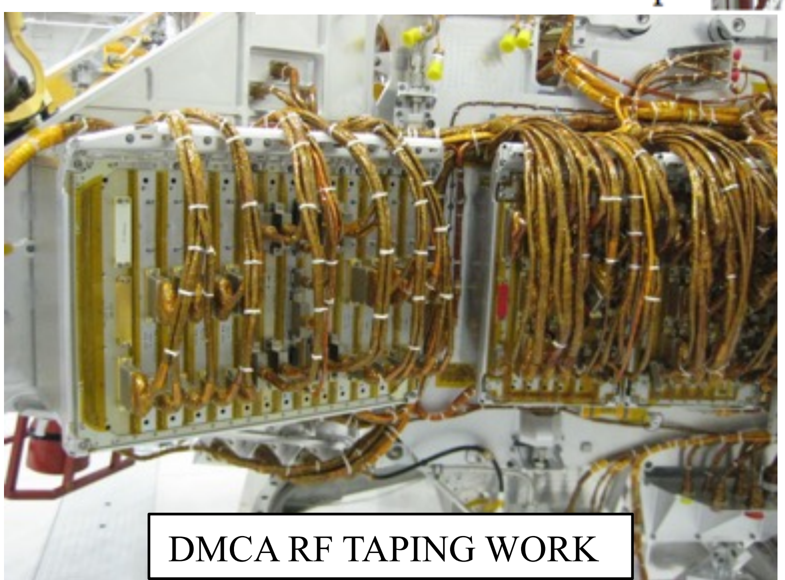
- Most JPL missions include sensitive instruments and RF receivers.
  - Limits on radiated emissions are imposed on other subsystems to reduce electromagnetic interference (EMI) on RF units.
- Radiated Emissions and Signal Integrity are considered together because they are strictly correlated.
  - Reflections of signals have the effect of increasing the radiated emissions from PCBs.
  - Switching noise produced by digital devices generate strong radiated emissions from cables attached to PCBs.
- Common mode noise increases a subsystem's radiated emissions profile and may interfere with nearby instruments and RF receivers.
  - Caused by skew, ringing, reflections, etc.
  - If operation of RF receiver and subsystem is simultaneous, impact can be significant, including loss of lock, false lock and performance degradation.

Enclosure Shielding - Seams and Penetrations





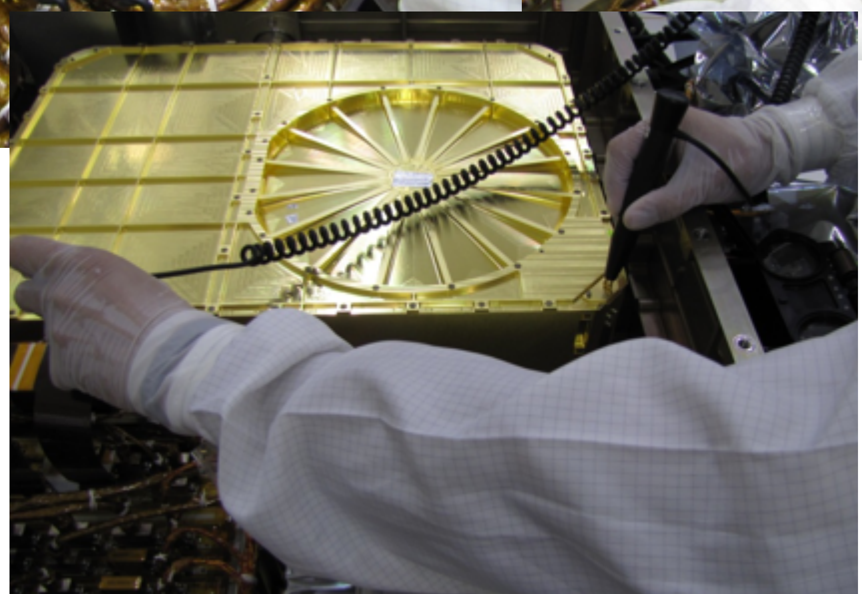
DMCA/DPAM RF Taped



DMCA RF TAPING WORK

DMCA RF TAPING WORK

Rover – Pre-Bellypan Install



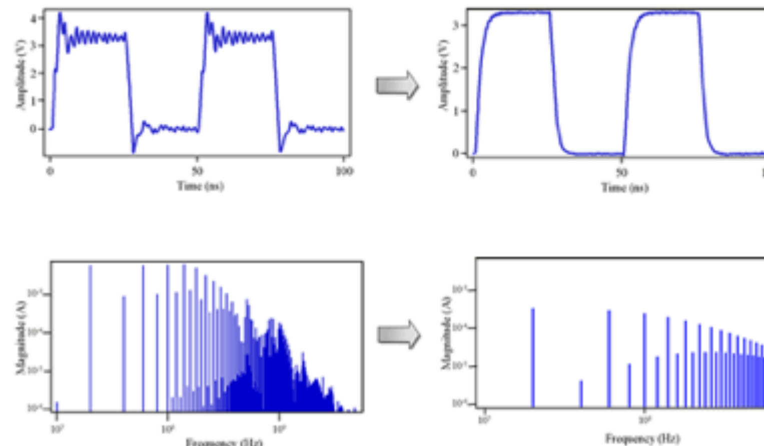
RF Frequency Domain Impact

Time Domain Signals Clashing With Frequency Domain RF Victims

High Speed Digital Signals

Sensitive RF Receivers

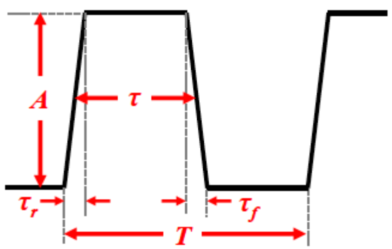
Time Domain

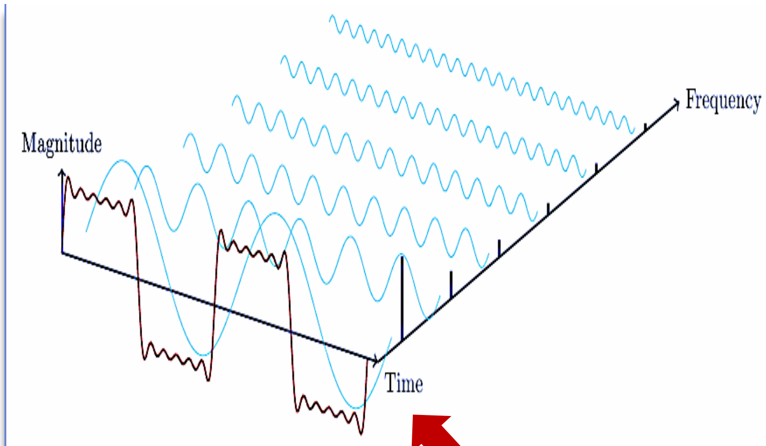


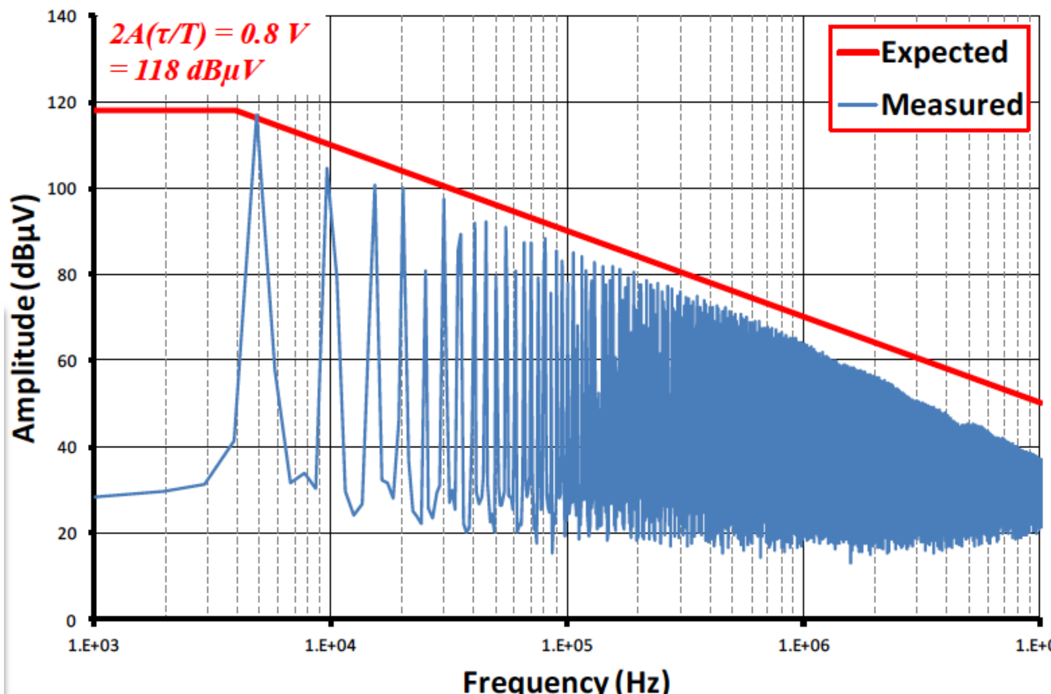
Frequency Domain

Radiated Emissions Example

TYPICAL SPECTRUM OF PULSE





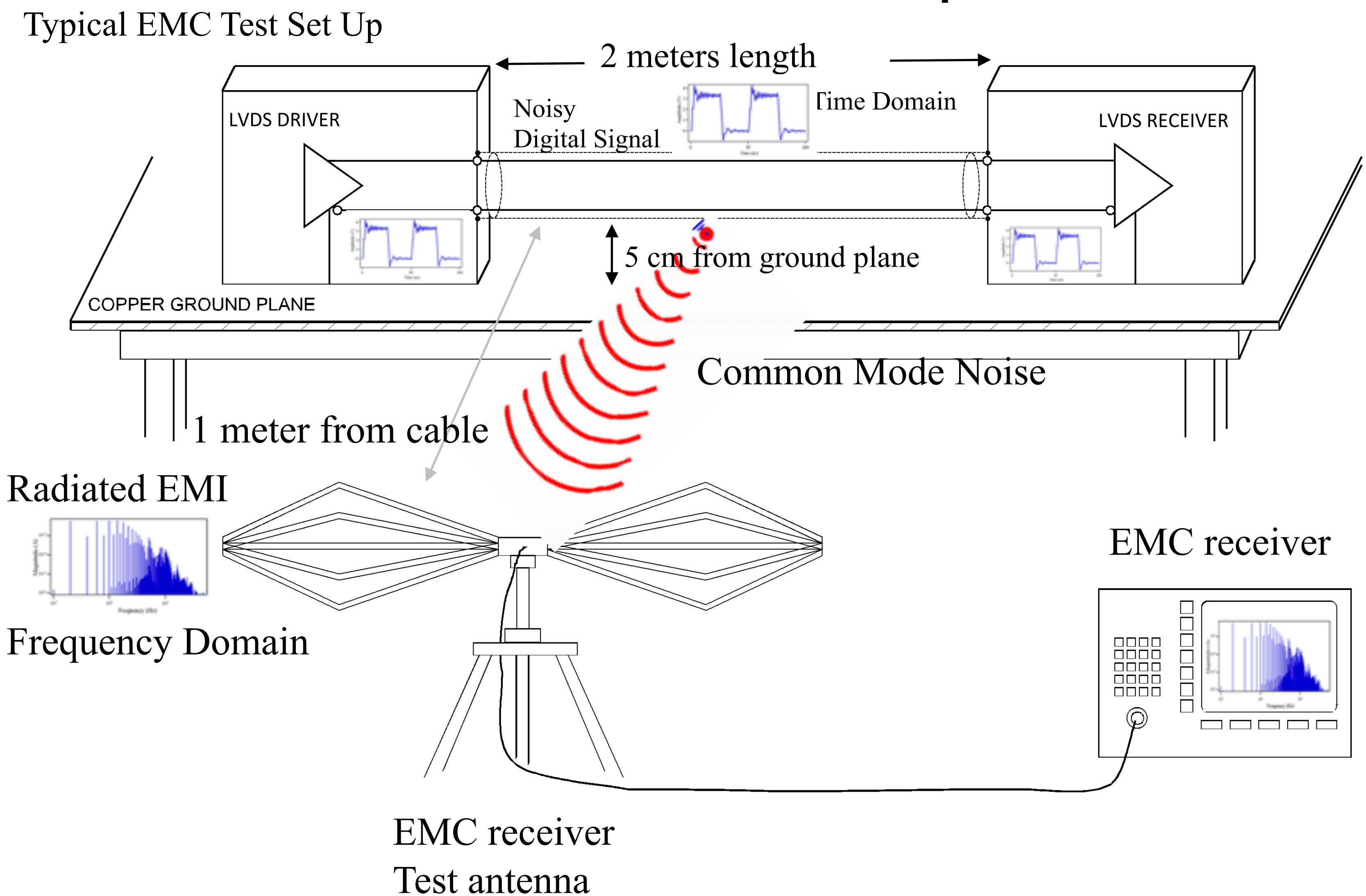


Time Domain Mapping Into Frequency Domain

Courtesy John McCloskey
EMC Chief Engineer
At NASA-GSFC

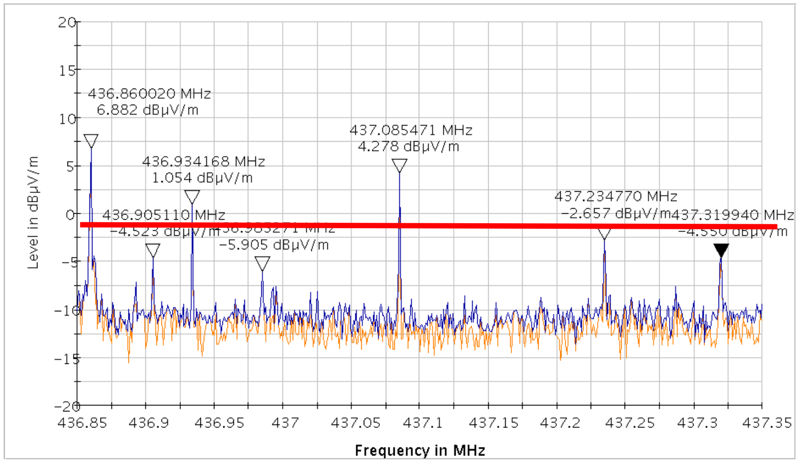
Radiated Electric Field Emissions

Radiated Emissions Example

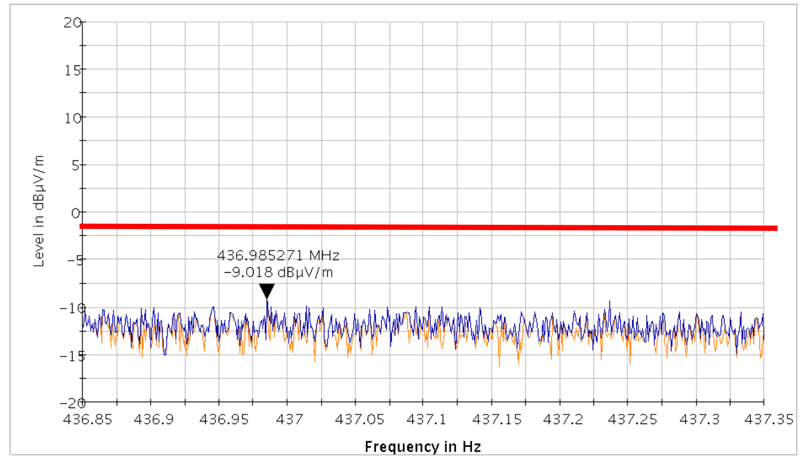


BACKUP/PLUGS OUT PROFILE

Rover Avionics ON



Channel 0, 437.1 MHz
Spec Limit -10 dB uV/m
Plugs In, Intermittent
False Locks



Channel 0, 437.1 MHz
Spec Limit -10 dB uV/m
Plugs Out, No False Locks

Radiated Emissions Example

Radiated Emissions In LVDS

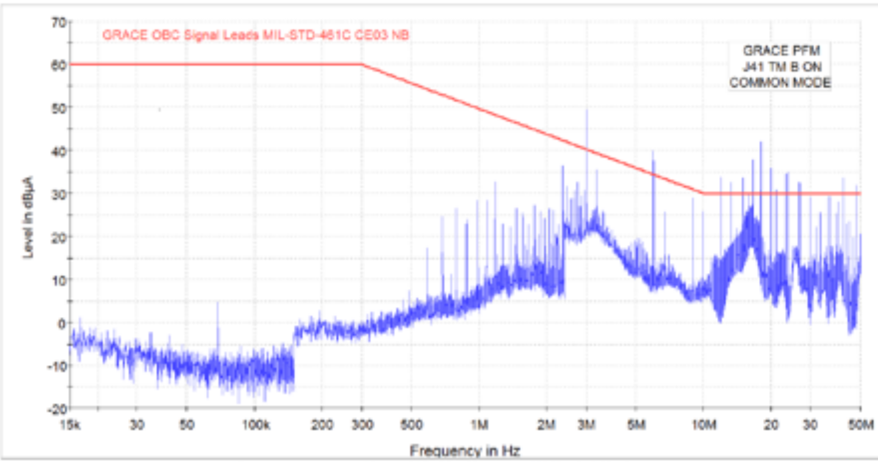
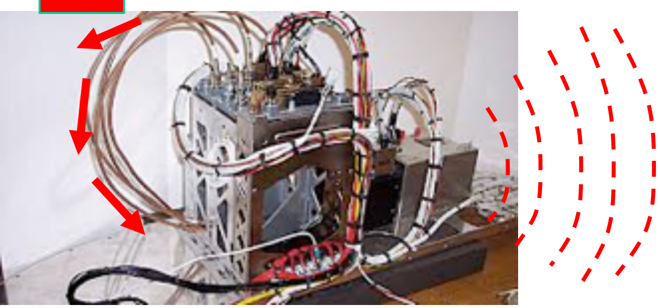


Figure 3.2-3. J41 CECM Data, PFM OBC

Common Mode Noise Works Its Way To Efficient Antenna Elements Such As Cables, Slots, Connectors Etc…

SI



EMI

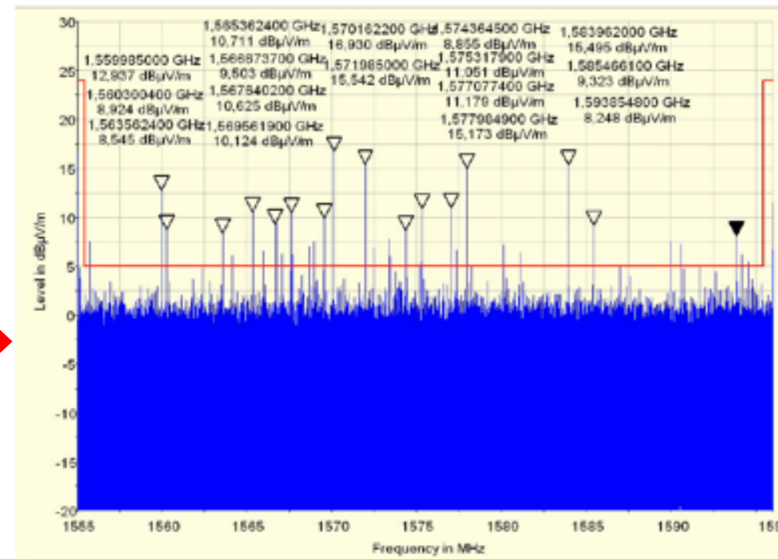
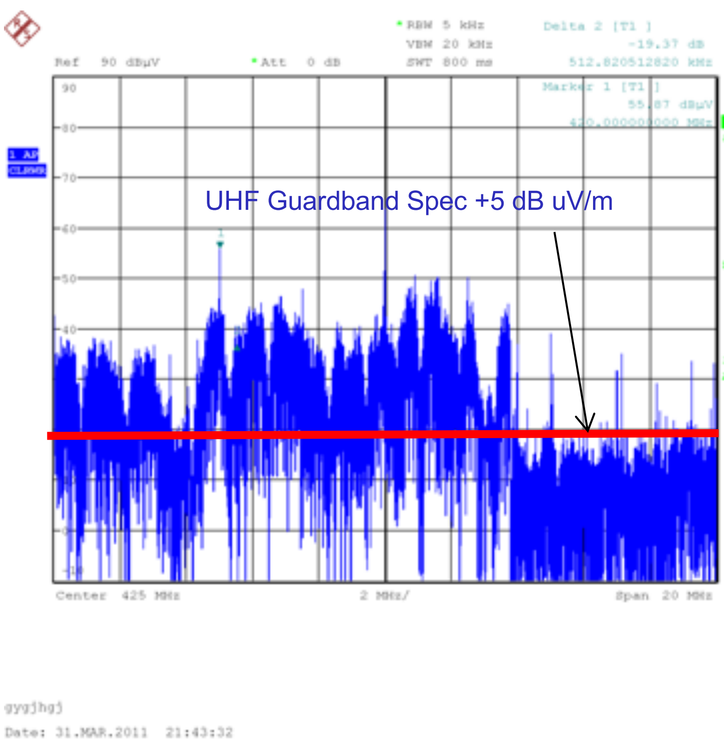


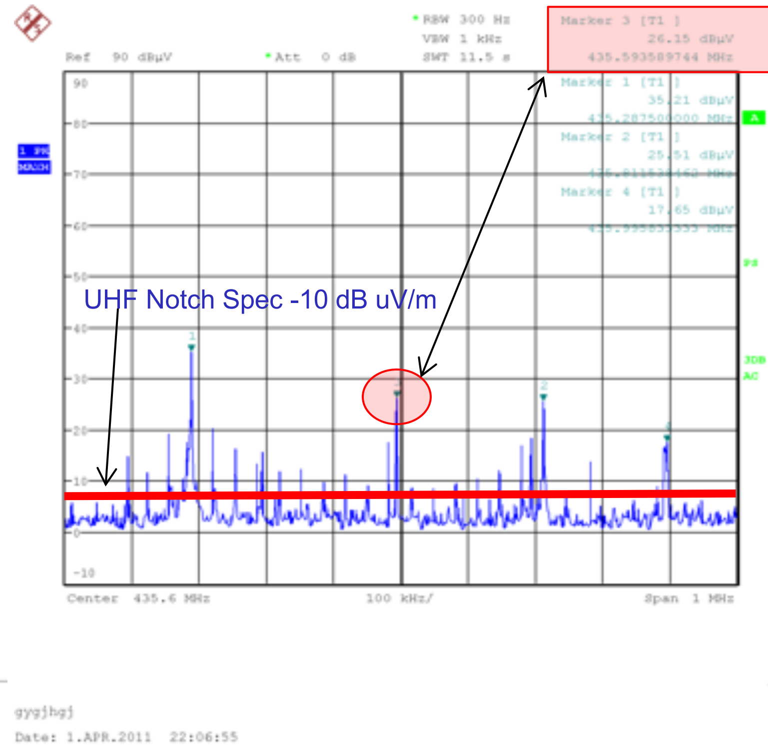
Figure 3.3-1. OBC PFM RE02 Data, GPS L1 Band, Vertical Polarity

…Resuting In Radiated Emissions In Sensitive Receiver Bands Such As GPS L1, Or UHF Or S-Band….

MARS CURIOSITY UHF INTERFERENCE PROFILE

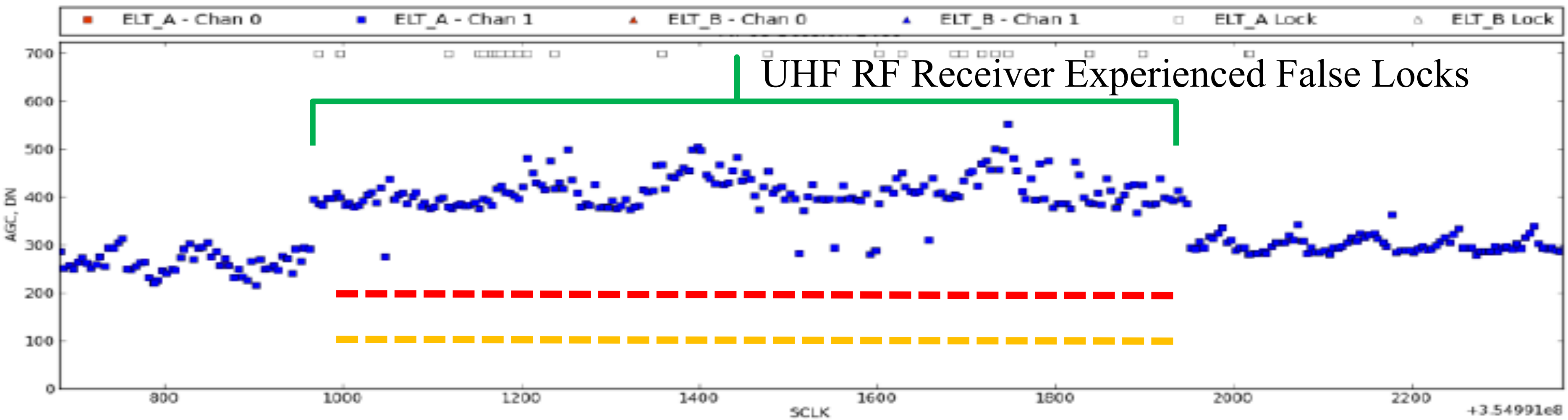


False Locks, MAHLI Camera On, General UHF Range



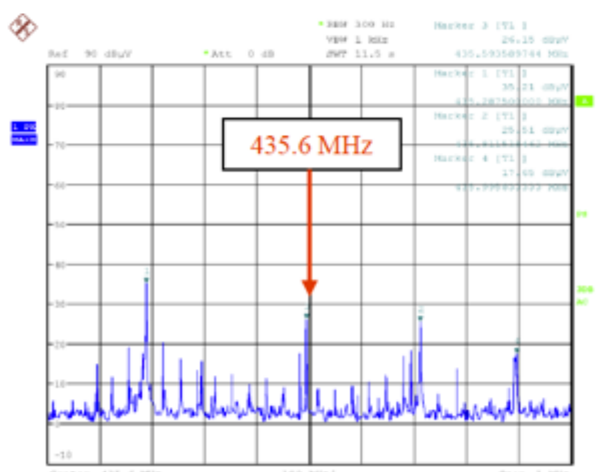
Channel 1, 435.6 MHz Other Cameras On, UHF False Locks

Some Lessons Learned – MSL Curiosity EMC System Test

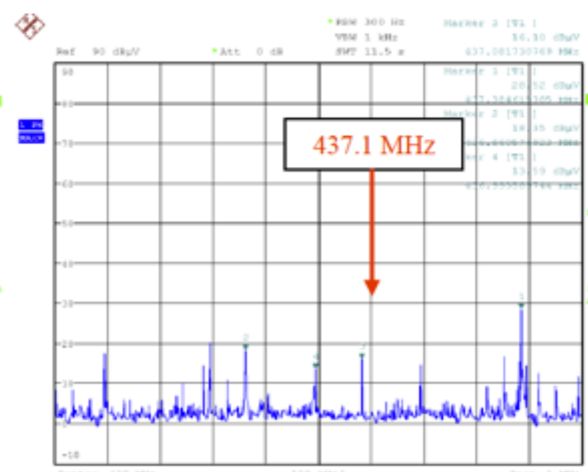


Cameras ON

UHF LOCK



(a) Channel 1



(b) Channel 0

UHF Ch

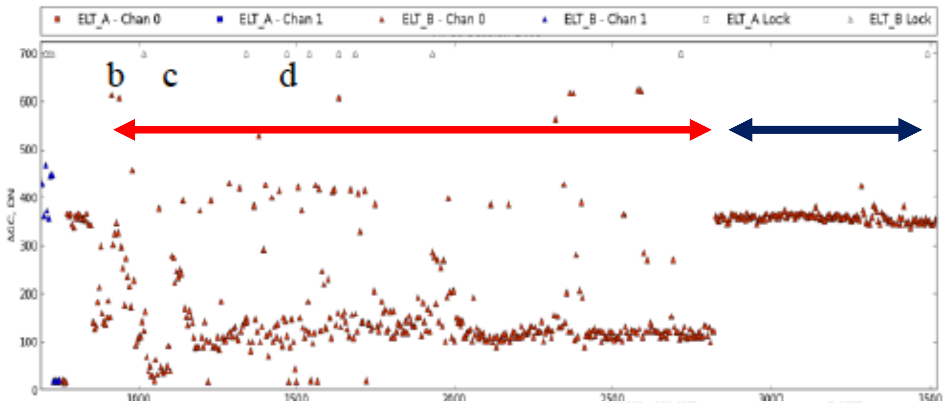
437.1 MHz

435.6 MHz

Some Lessons Learned – MSL EMC System Test

- **Curiosity UHF Radio Experienced Electromagnetic Interference From Engineering Cameras: Loss Of Lock, False Locks and AGC Fluctuations**

AGC Fluctuations When Cameras On

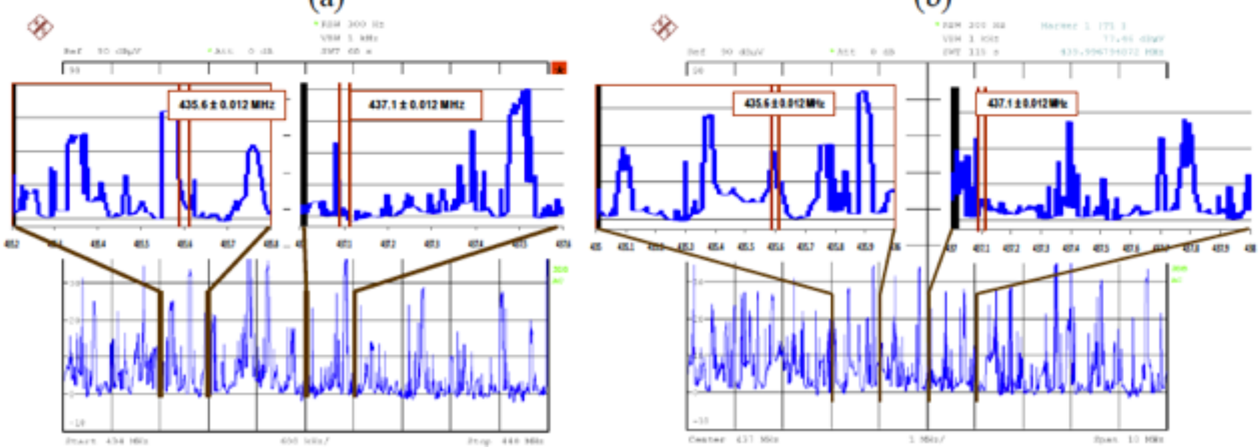


AGC Stable When Cameras Off

(a)

(b)

CAMERAS ON



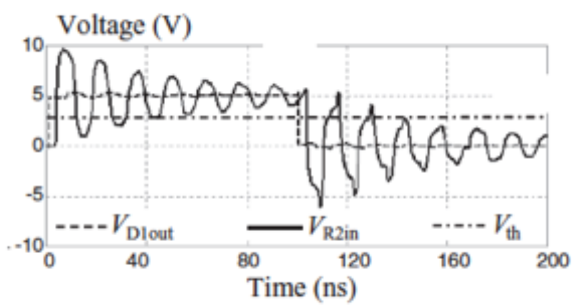
UHF Ch

437.1 MHz

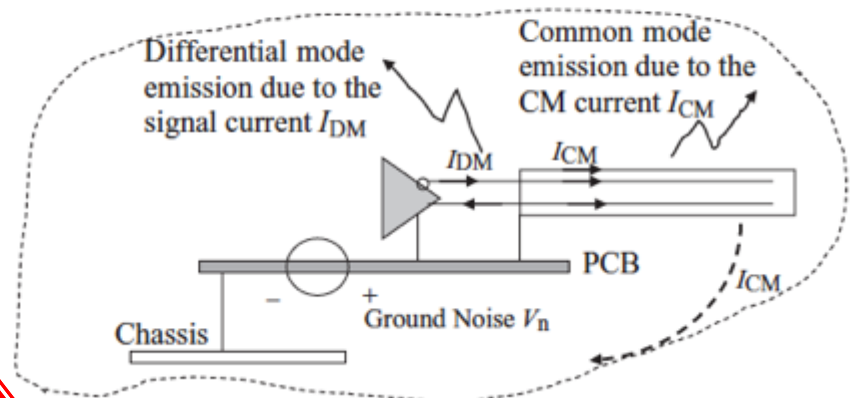
435.6 MHz

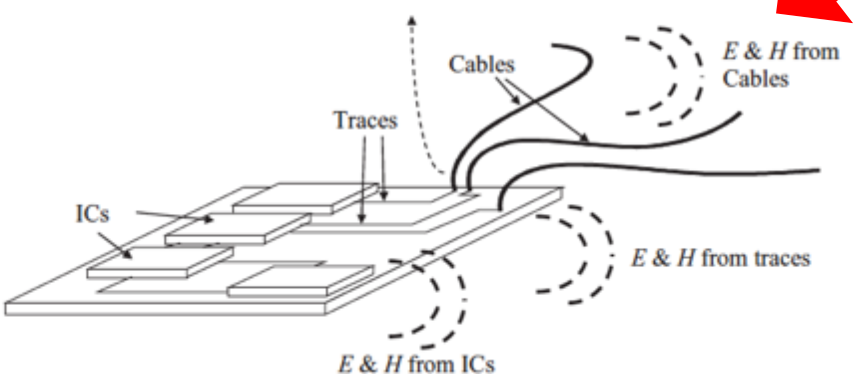
Common Mode Noise = RE

Poor Signal Integrity PCB Design….



Leads To Common Mode Noise…





Which Leads To PCB Radiated EMI Noise

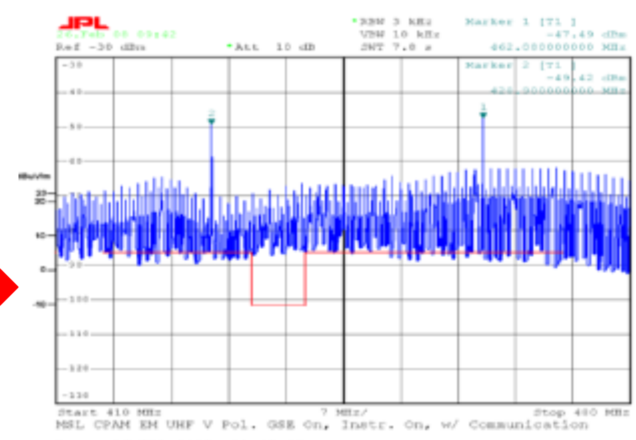
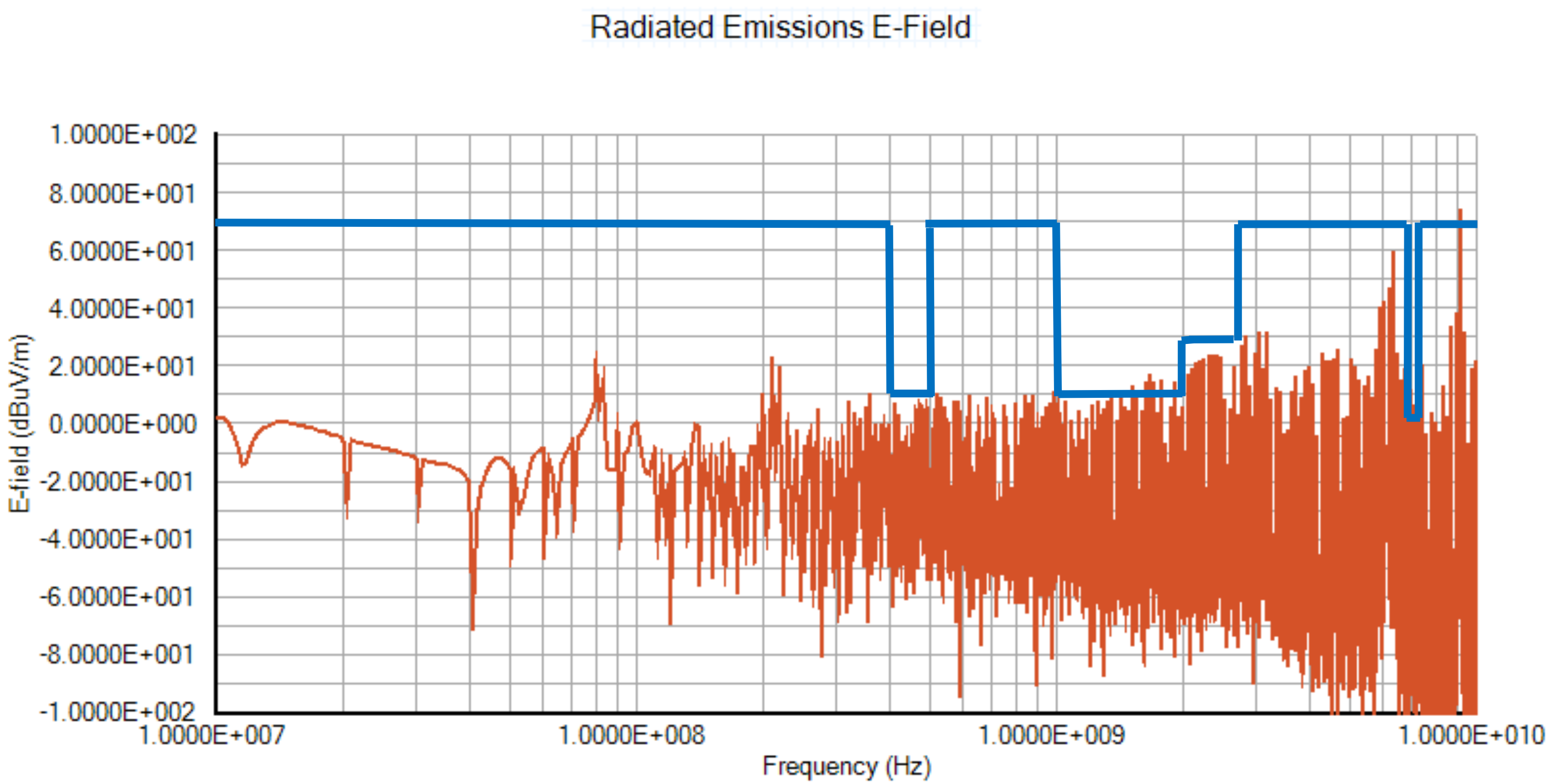


Figure 65, Follow-on diagnostics, UHF notch, 410 – 480 MHz, vertical polarization

Impacting Sensitive RF Receivers

RE Results for Condition 2 – Bad SI Design

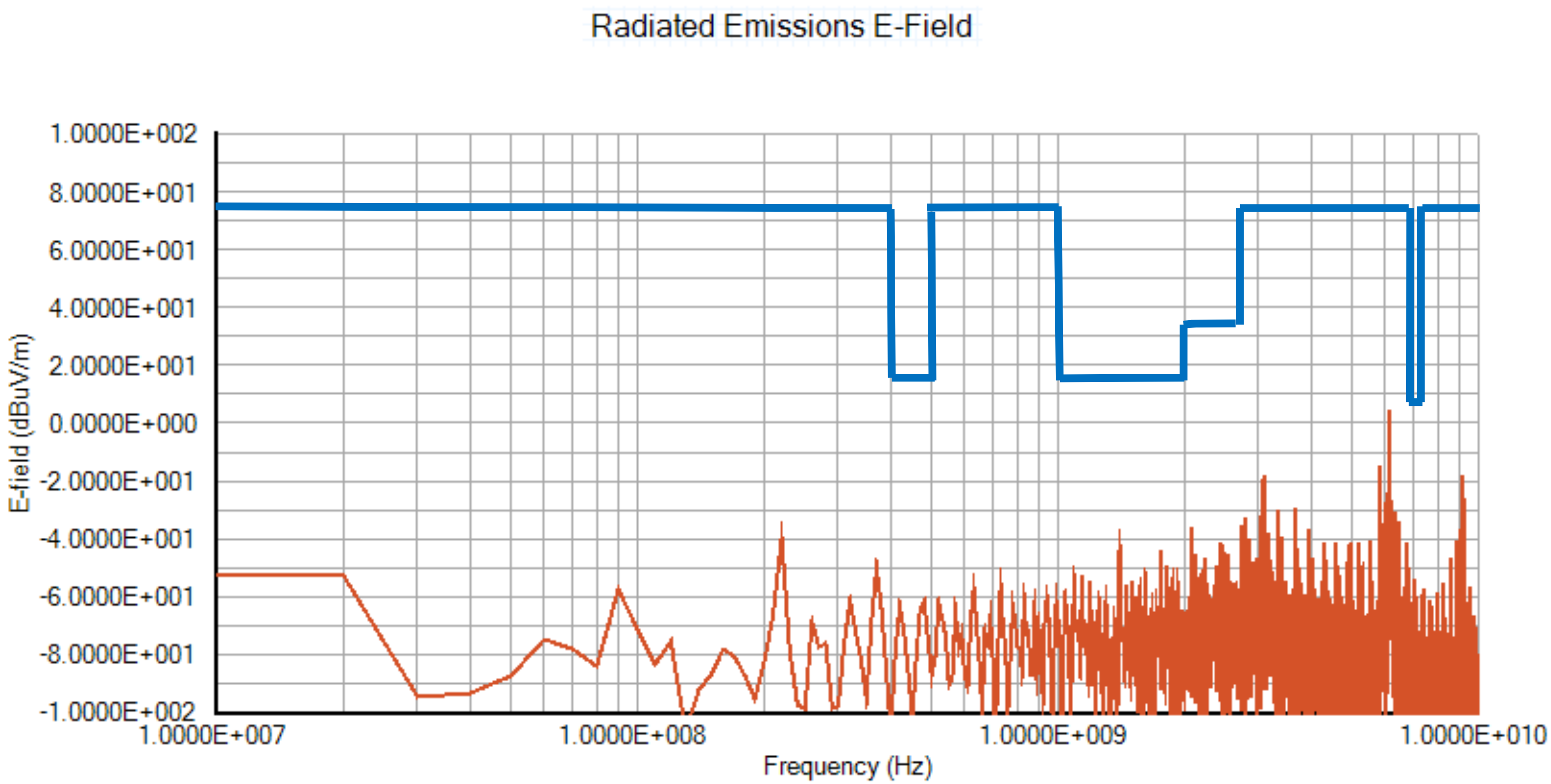
Braid Shielded Cable, with 200 picoSec Skew and CM Noise



Bad SI Design Produces Common Mode Noise Which Produces Significant Radiated Emissions

RE Results for Condition 1 – Good SI Design

Braid Shielded Cable, No Skew, No CM Noise



Good SI Design Eliminates Common Mode Noise Which Reduces Radiated Emissions

PCB Physical Geometry Creates The Amount Coupling Between Noisy Circuits and Structures (Ground Planes, Chassis, Cables) …

...Due To Parasitic Capacitance And Inductance That Exists Within These Structures…

Capacitance and Inductance Is The Main Mechanism…

…That Produces Noise Due To dV/dt and dI/dt Switching Conditions…

…Generating Unwanted Common Mode Noise Flowing On Cables/Structures and Thus …

Producing Unwanted Radiated Emissions

<u>REDUCE RADIATED EMISSIONS</u> By Managing PCB Physical Geometry.
<u>MINIMIZE COMMON MODE NOISE</u> By Controlling Trace Layout, Ground Planes, Edge Rates, Ringing, Overshoot/Undershoot,

EMI Shielding

- Shielding
  - Why Do We Shield?
  - Cable Shielding
  - Skin Depth
  - Enclosure Shielding

SAC-D/Aquarius RE Requirements

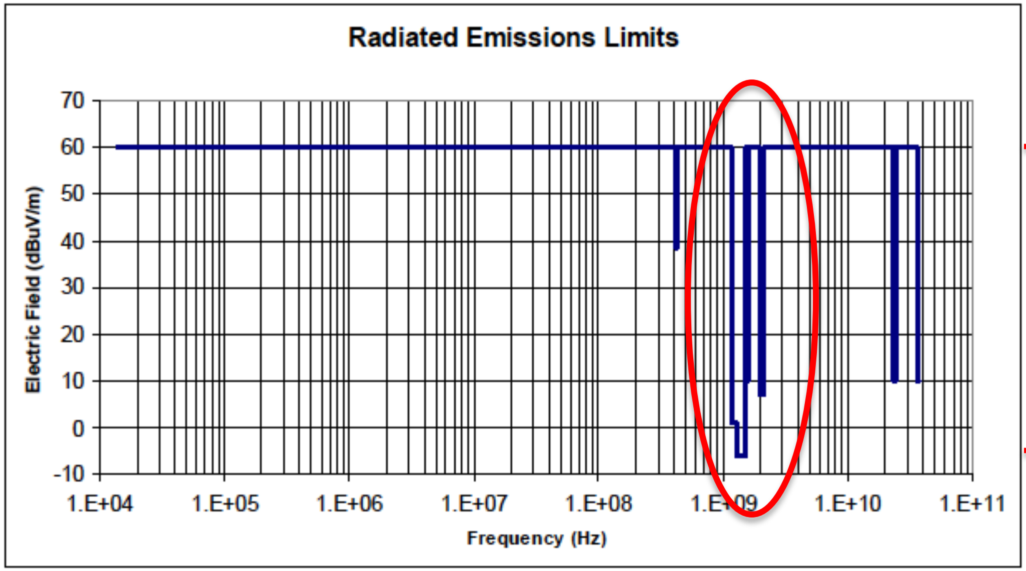
Table 3- 1: Aquarius Radiated Emissions E-Field Specification Levels @ 1 meter

L2B-AS-c-889

Frequency Range	Electric Field Limit	Potential Victim
14 kHz to 18 GHz	60 dBµV/m	Baseline Maximum Allowable Radiated Emissions Limits
408 to 430 MHz	36 dBµV/m	Launch Vehicle Command/Destruct UHF Rx Protection Band
461.62 MHz +/- 15 kHz	20 dBµV/m	DCS +Z UHF Omni
1300 to 1500 MHz	-6 dBµV/m	Aquarius L-Band Radiometer
1160 to 1360 MHz	1 dBµV/m	Aquarius L-Band Scatterometer
1217 to 1238 MHz	10 dBµV/m	GPS L2 Receiver (TDP & ROSA)
1565 to 1586 MHz	10 dBµV/m	GPS L1 Receiver (Navigation)
2035 MHz +/-60 KHz	7 dBµV/m	SAC-D S Band Uplink TC
23.3 to 24.3 GHz	10 dBµV/m	CONAE MWR K-Band
36.4 to 37.6 GHz	10 dBµV/m	CONAE MWR Ka-Band

Huge Challenge
Most Stringent
Specs To Date
Never Attempted
At JPL

L2B-AS-c-890



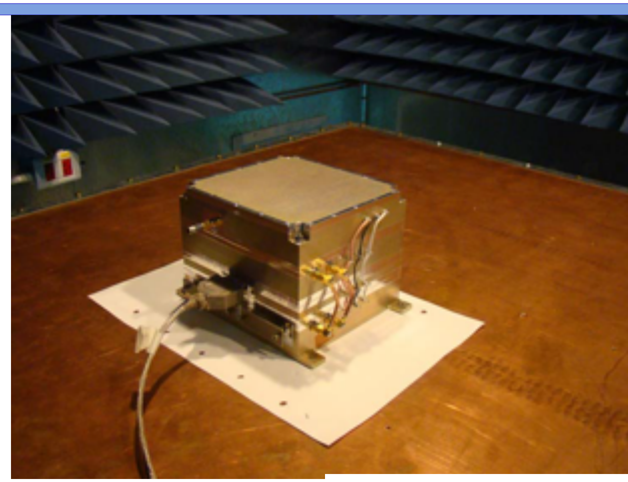
Notch
66 dB
Drop
From
General
Spec Limit

SAC-D/Aquarius RE Requirements

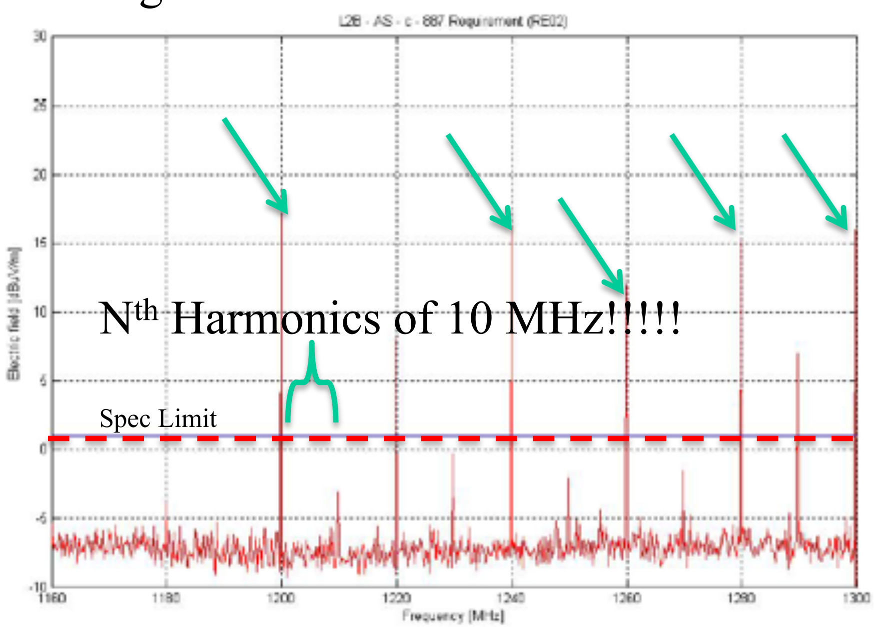
A narrowband EMI source has an effective noise temperature

$$dT_N = \frac{dP_{EMI}}{kB}$$

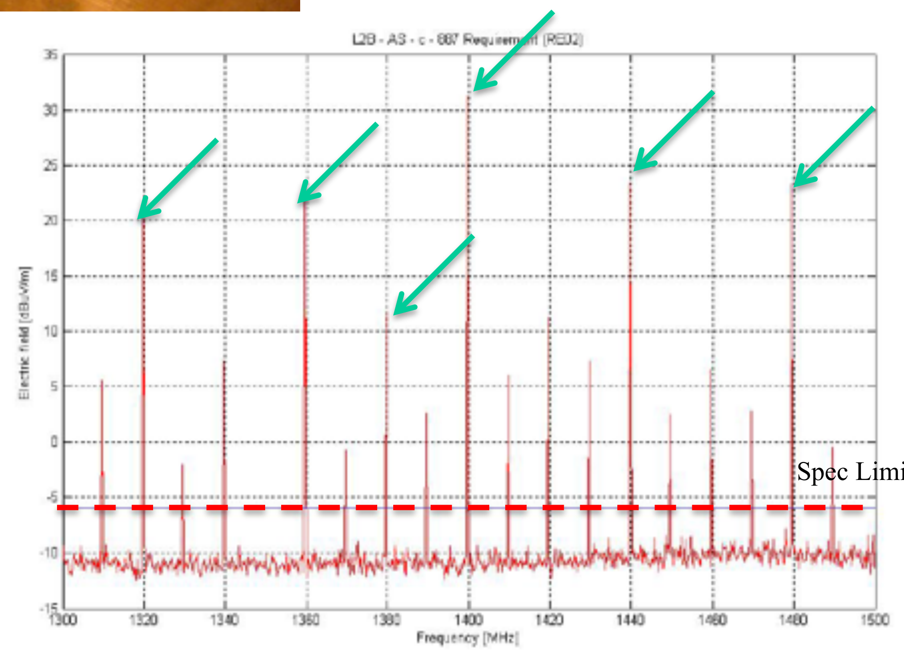
Radiometer can detect this “Signal” if it is large enough



Typical SAC-D Box Digital Collection System (DSC)



Scatterometer Band



Radiometer Band

Bonding - NASA-STD-4003

NASA-STD-4003
September 8, 2003

TABLE I. Summary of Electrical Bonding Classes

	Power Return	Shock Hazard	Radio Frequency	Lightning	Electrostatic Charge
BOND CLASS	CLASS "C"	CLASS "H"	CLASS "R"	CLASS "L"	CLASS "S"
PURPOSE OF BOND	Reduces power and voltage losses. Applies to equipment & structure, which are required to return intentional current through structure.	Protects against fire or shock to personnel. Applies to equipment & structure that may be required to carry fault current in case of a short to case or structure.	Protects equipment from RF emissions. Applies to equipment that could generate, retransmit, or be susceptible to RF. Includes antenna mounts and cable shield connections. Covers wide frequency range.	Protects equipment from lightning effects. Applies to equipment or structure that would carry current resulting from a lightning strike.	Protects against electrostatic discharge. Applies to any item subject to electrostatic charging.
BOND REQT.	Requires low impedance & low voltage across joints to assure adequate power to the user. Jumpers and straps acceptable.	Requires low impedance & low voltage across joints to prevent shock hazard or fire due to short. Jumpers and straps acceptable.	Requires low RF impedance at high frequency. Direct contact preferred. No jumpers. Short, wide strap may be used as last resort.	Requires low impedance at moderate frequency. Bonding components must withstand high current. Straps and jumpers must withstand high magnetic forces.	Allows moderate impedance. Jumpers and straps acceptable.
DC BOND RESISTANCE REQT.	Bonding resistance requirement depends on current.	Bonding resistance requirement, 0.1 ohm or less. Special requirements when near flammable vapors.	Bonding resistance requirement, 2.5 milliohms or less. Low inductance required.	Bonding resistance requirement depends on current. 500 volts or less across any joint. Low inductance required.	Typical bonding resistance requirement, 1.0 ohm or less.
FREQ. REQT.	Low	Low	High	High	Low
CURRENT REQT.	High	High	Low	High	Low

Low frequency bonds allow use of straps and jumpers.
High frequency bonds require low inductance paths. Short straps are sometimes acceptable.
High current bonds require large cross sectional areas.
Low current bonds allow use of small contact areas.

Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Bonding – Class H (Shock and Fault Protection)

- From NASA-STD-4003, Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment:
  - <u>4.2 Shock and Fault Protection (Class H) – excerpts:</u>
    - All electrically conductive equipment cases that may develop potentials due to short circuits shall be electrically bonded to structure.
    - Bonding of structural joints in the fault current return path shall provide for the maximum current that may be delivered by the power supply until the fuse or circuit breaker disconnects.
    - Exposed cases or chassis of electrical or electronic equipment shall be bonded to structure with a resistance of 0.1 ohm or less.

Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

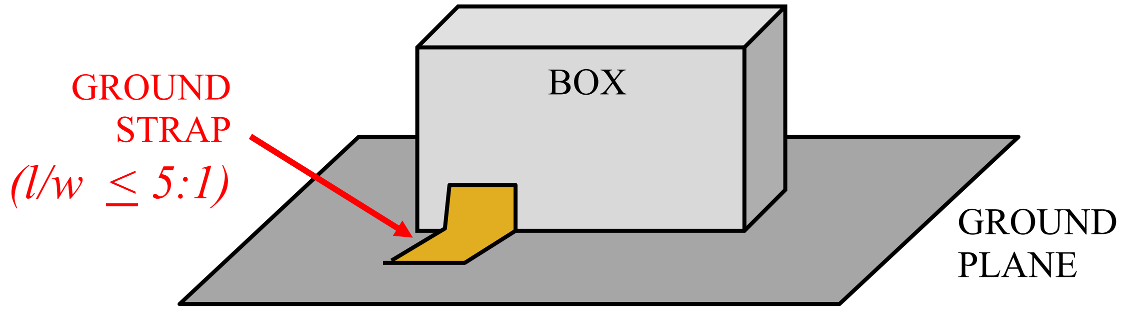
Bonding – Class R (Radio Frequency)

- **From NASA-STD-4003, Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment:**
  - **<u>4.3 Electromagnetic Interference or Radio Frequency (Class R) – excerpts:</u>**
    - **RF bonding is required between all conductive basic structural components of the vehicle.**
    - **The dc resistance across each joint shall not exceed 2.5 milliohms.**
    - **The dc resistance from equipment case to structure shall not exceed 2.5 milliohms.**

Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Bonding – Class R (cont.)

- **From NASA-STD-4003, Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment:**
  - **6.4 Electromagnetic Interference or Radio Frequency (Class R):**
    - **There is no RF design basis for the historical 2.5-milliohm requirement except to ensure a good metal-to-metal contact that can be expected to be consistent.**
    - **If the use of bond straps for RF bonds is unavoidable, strap length should always be limited to a length to width ratio of 5 to 1.**
    - **The 2.5-milliohm, dc resistance requirement is good for a standard, but one should not assume a good RF bond exists just because the dc resistance is less than 2.5 milliohms. Also, extra effort need not be made just to satisfy the dc requirement if the RF impedance is much higher due to the inductance of the configuration. Look at the whole configuration to get the lowest impedance possible at the frequencies of interest to produce a good RF bond.**



Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Bonding Summary

- Class H
  - Shock and Fault Protection
  - 0.1 ohm
  - Must have current capacity to withstand worst-case fault current
- Class R
  - Radio Frequency (RF)
  - 2.5 milliohms
  - Direct metal-to-metal contact preferred
  - If a strap is used, use minimum length-to-width ratio of 5:1
    - Much less inductance than wire
    - Multiple straps recommended (one on each face of box)

Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

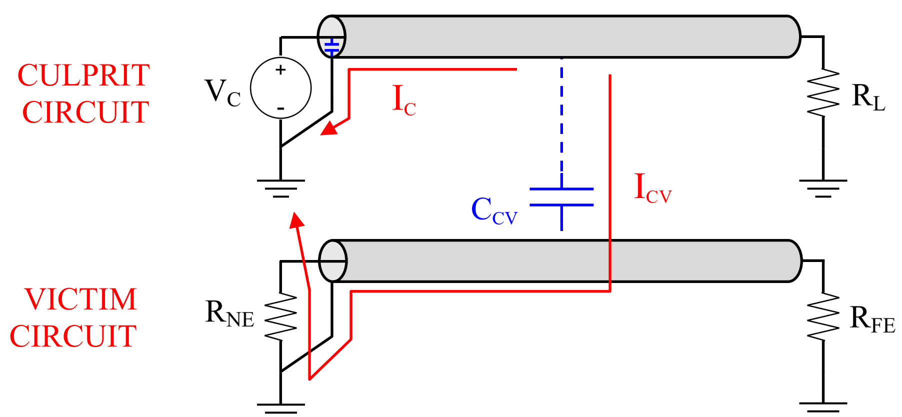
Why Do We Shield?

- **Purpose of shielding:**
  - **Contain emissions from noisy circuits**
  - **Protect signal carrying conductors from interference**
- **Remember Kirchoff's Current Law:**
  - **All currents return to their sources following path of least impedance**
- **Shield's raison d'être:**
  - **Provide return path to the source over the lowest impedance (most desirable) path possible**
  - **Direct current back to source and away from sensitive circuitry**

Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

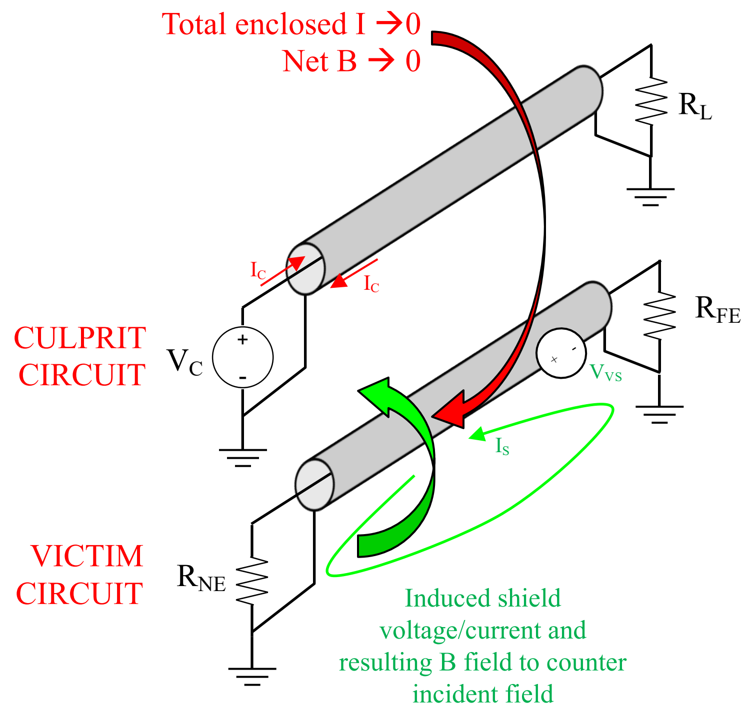
Cable Shielding - Capacitive Coupling

- Emissions
  - Culprit current couples to its own shield and returns to its source
- Susceptibility
  - Any remaining current that makes its way to victim couples to victim's shield and gets shunted back to source (via ground), protecting victim signal wire
- Shields must provide low impedance path back to source
  - Includes shield terminations, connector to chassis connections, reference plane to chassis connections, etc.



Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Cable Shielding - Inductive Coupling

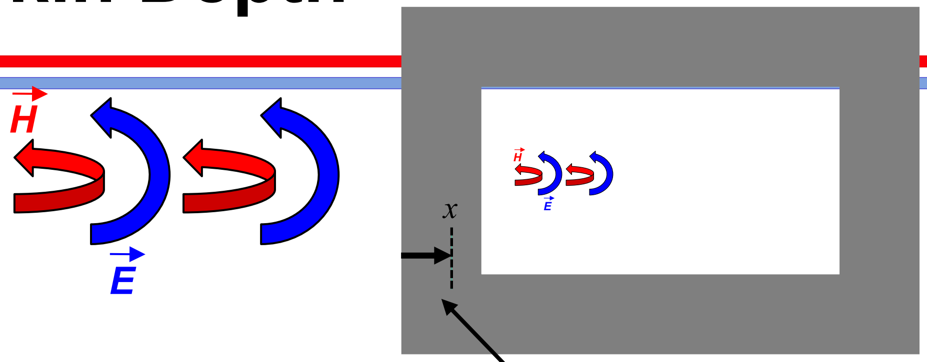


- **Emissions**
  - **Provides return current path to cancel culprit current**
  - **Reduced net current reduces net magnetic field**
- **Susceptibility**
  - **Reduced loop area**
  - **Any remaining B field induces V and I in shield to counter incident field**
  - **Shield must be terminated at both ends to allow current to flow**
  - **Drawback: Can induce secondary coupling onto victim wire**
  - **Internal twisted pairs recommended for additional magnetic field protection**

SHIELDING CAN HELP MITIGATE INDUCTIVE COUPLING, BUT IT IS GENERALLY NOT SUFFICIENT (INTERNAL TWISTED PAIRS RECOMMENDED FOR ADDITIONAL PROTECTION)

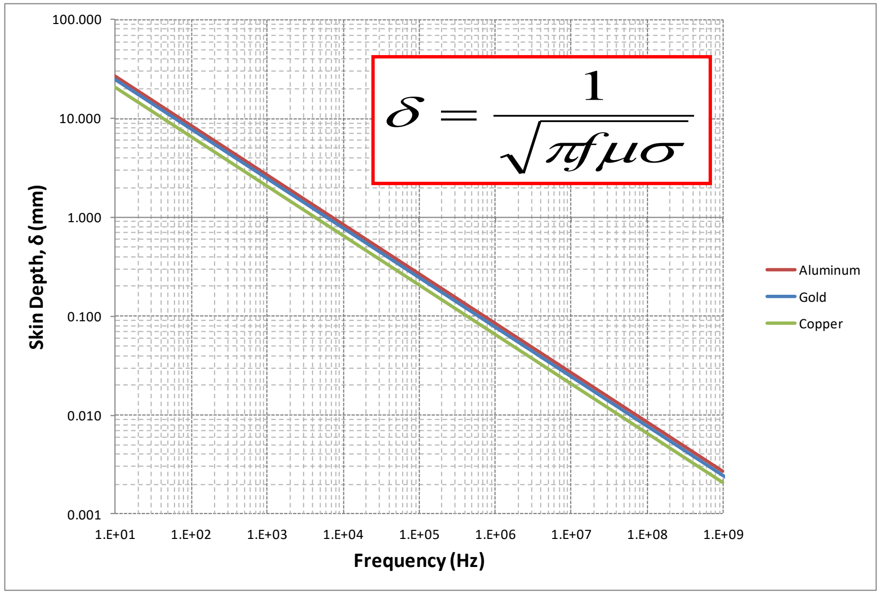
Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Skin Depth

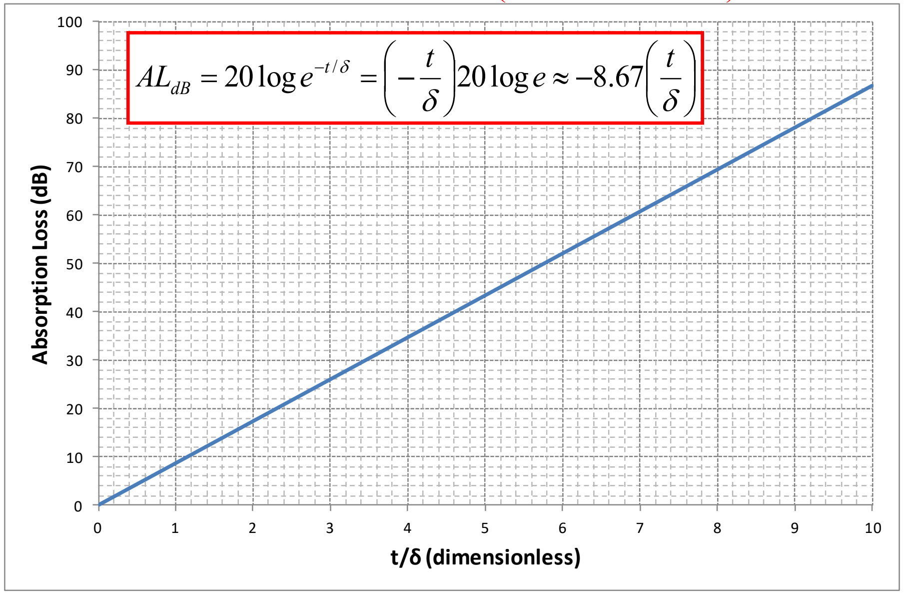


$$E(x) = E_{in} e^{-x/\delta}$$
$$H(x) = H_{in} e^{-x/\delta}$$

SKIN DEPTH



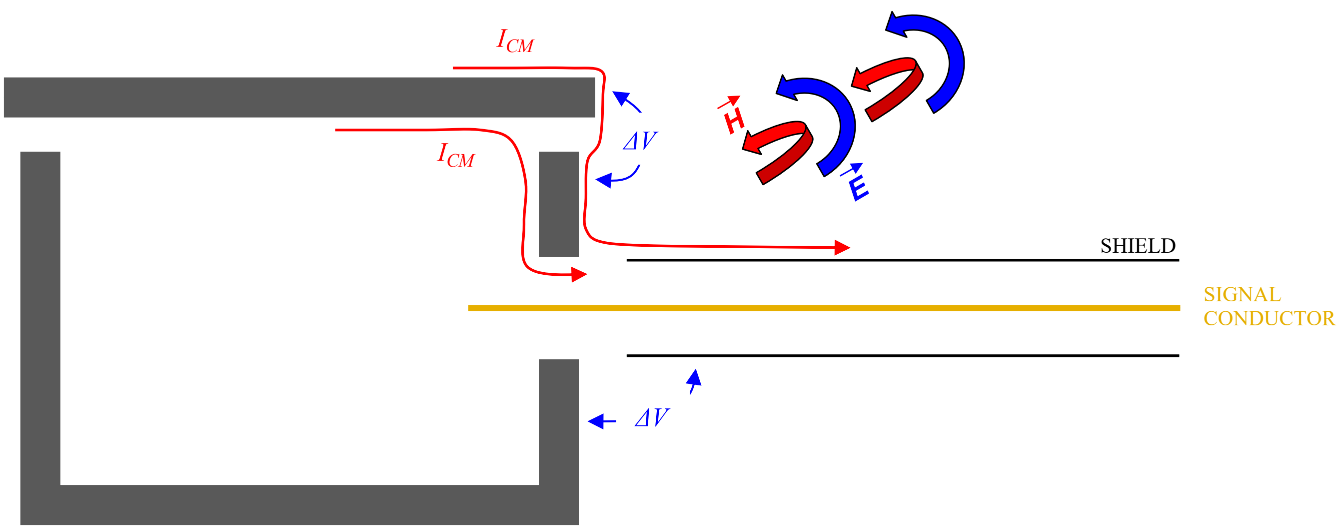
ABSORPTION LOSS (ATTENUATION)



100 mils (2.54 mm) of aluminum provides > 80 dB attenuation above 100 kHz

Enclosure Shielding - Seams and Penetrations

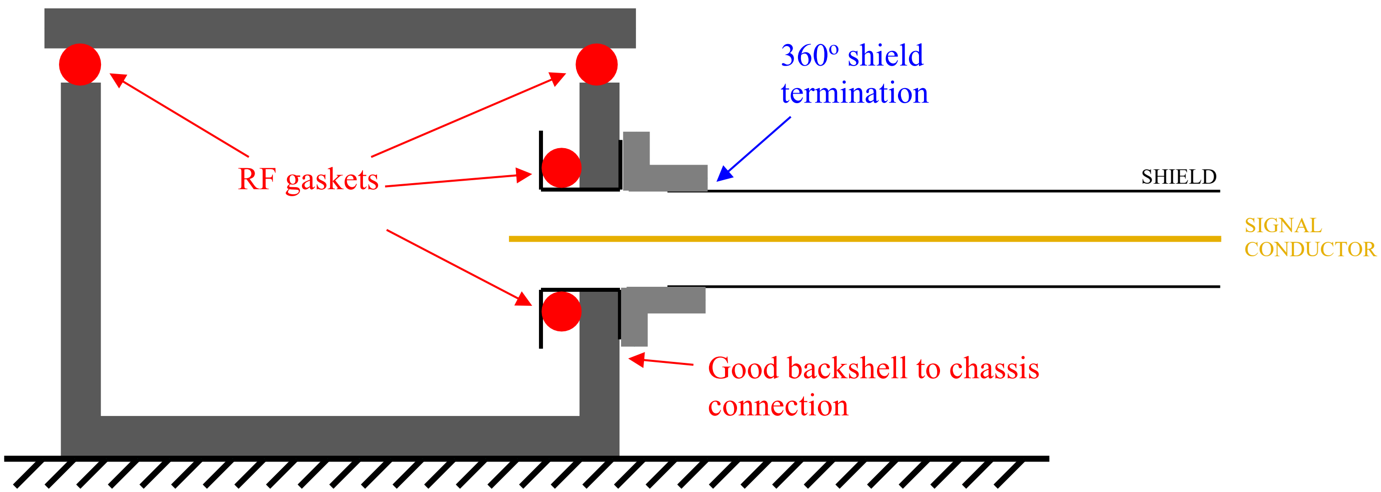
- Metal chassis provides darned good shielding (previous slide)
- Weak point always comes at seams and penetration points
  - Poor connections allow ΔV between conductors (antenna)
  - ΔV induces common mode current (I_{CM}) across connection impedance
  - I_{CM} induces radiated fields



Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Enclosure Shielding - Seams and Penetrations (cont.)

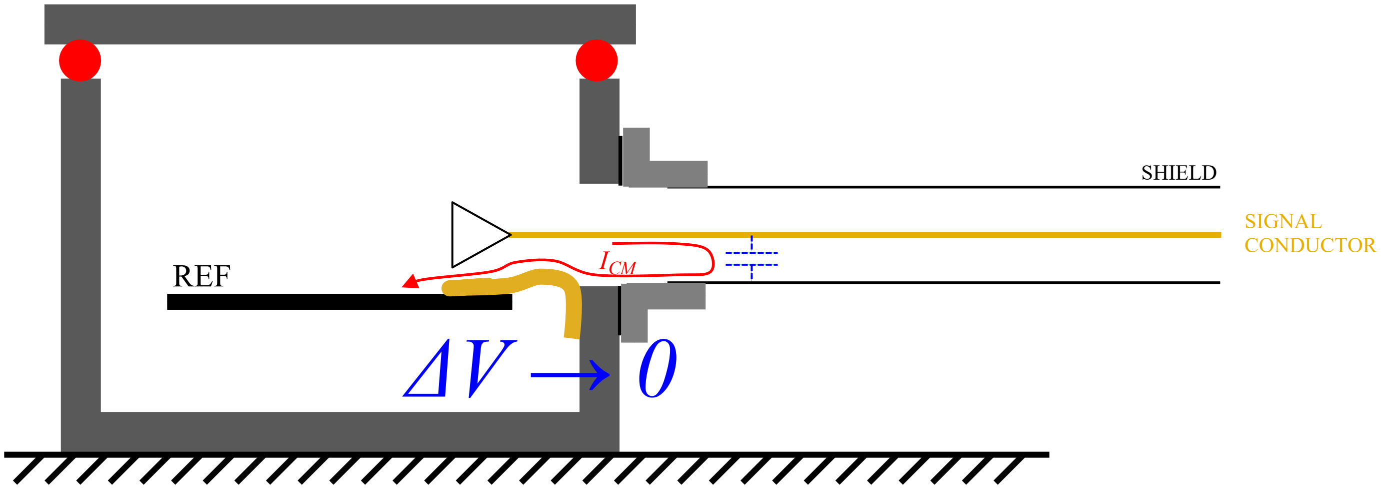
- Good metal-to-metal contact is essential
  - RF gaskets on all seams and penetrations
  - 360° termination of shield to backshell **(NO PIGTAILS!!!)**
  - Good metal-to-metal contact between backshell and chassis
  - **Class R bonds**



Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Enclosure Shielding - Seams and Penetrations (cont.)

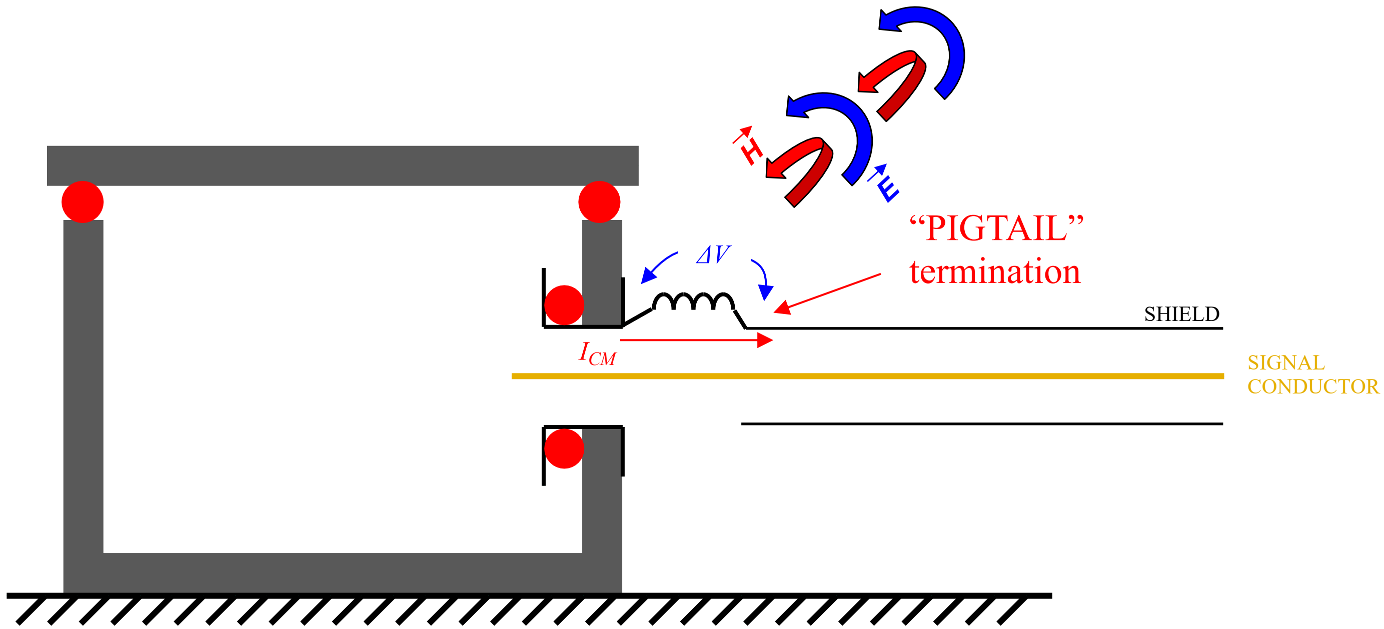
- Reference planes should be bonded to chassis at I/O connector(s)
  - Provide low impedance path for currents to return to source
  - Minimize ΔV between reference plane and chassis
  - Reduce radiated emissions



Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Enclosure Shielding - Seams and Penetrations (cont.)

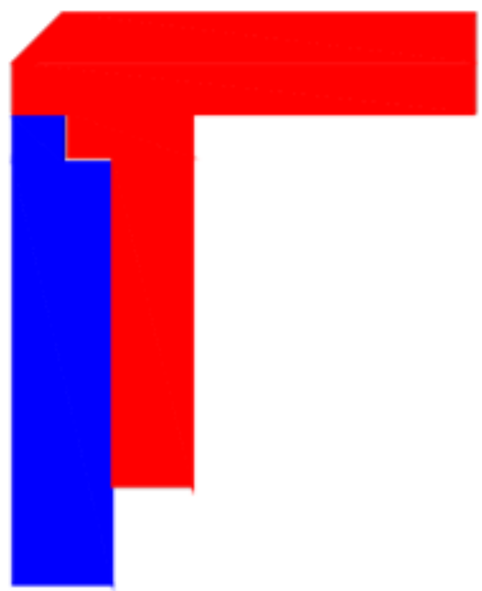
- "Pigtail" termination has significant inductance
- Allows ΔV between conductors (antenna)
- ΔV induces common mode current (I_{CM}) across connection impedance
- I_{CM} induces radiated fields



Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Enclosure Shielding - Seams and Penetrations (cont.)

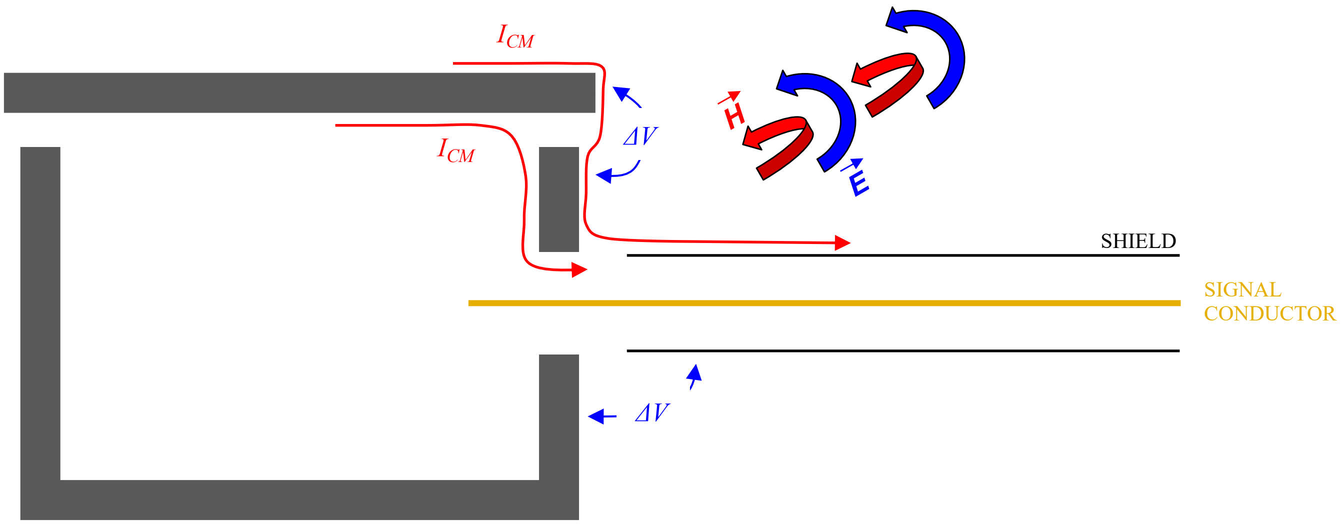
- Alternative for panel to panel seams
  - Minimum of 2 right angle turns (“labyrinth”)
  - Electromagnetic energy has to “work” harder to get through seam



Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

Enclosure Shielding - Seams and Penetrations

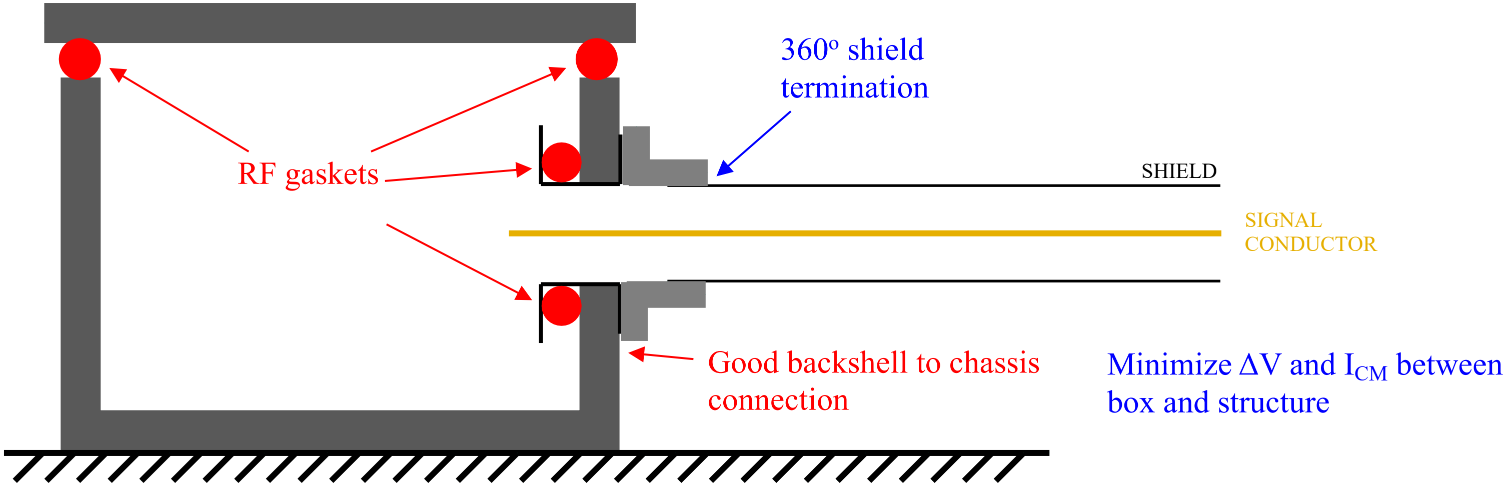
- Metal chassis provides very good shielding (previous slide)
- Weak point always comes at seams and penetration points
  - Poor connections allow ΔV between conductors (antenna)
  - ΔV induces common mode current (I_{CM}) across connection impedance
  - I_{CM} induces radiated fields



Courtesy of John McCloskey NASA-GSFC

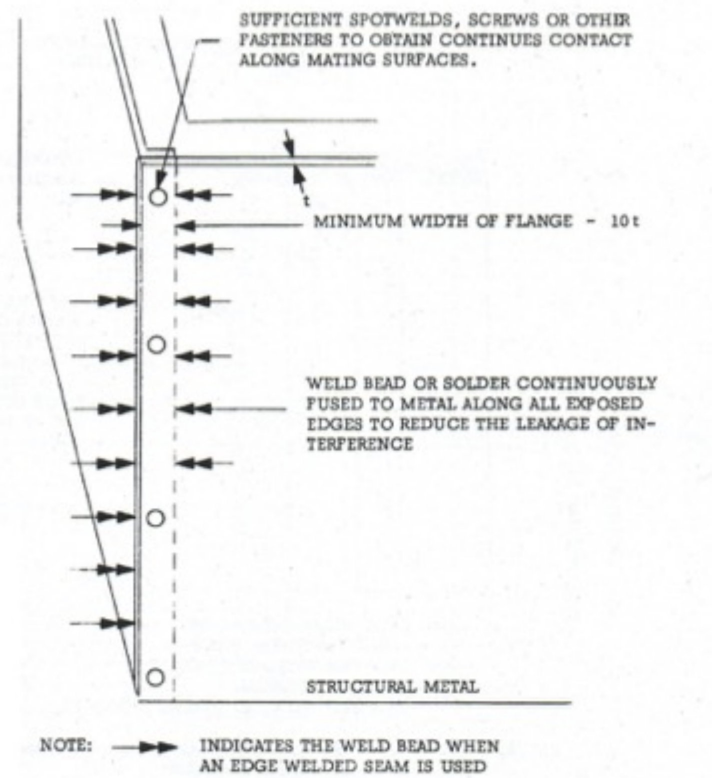
Enclosure Shielding - Seams and Penetrations (cont.)

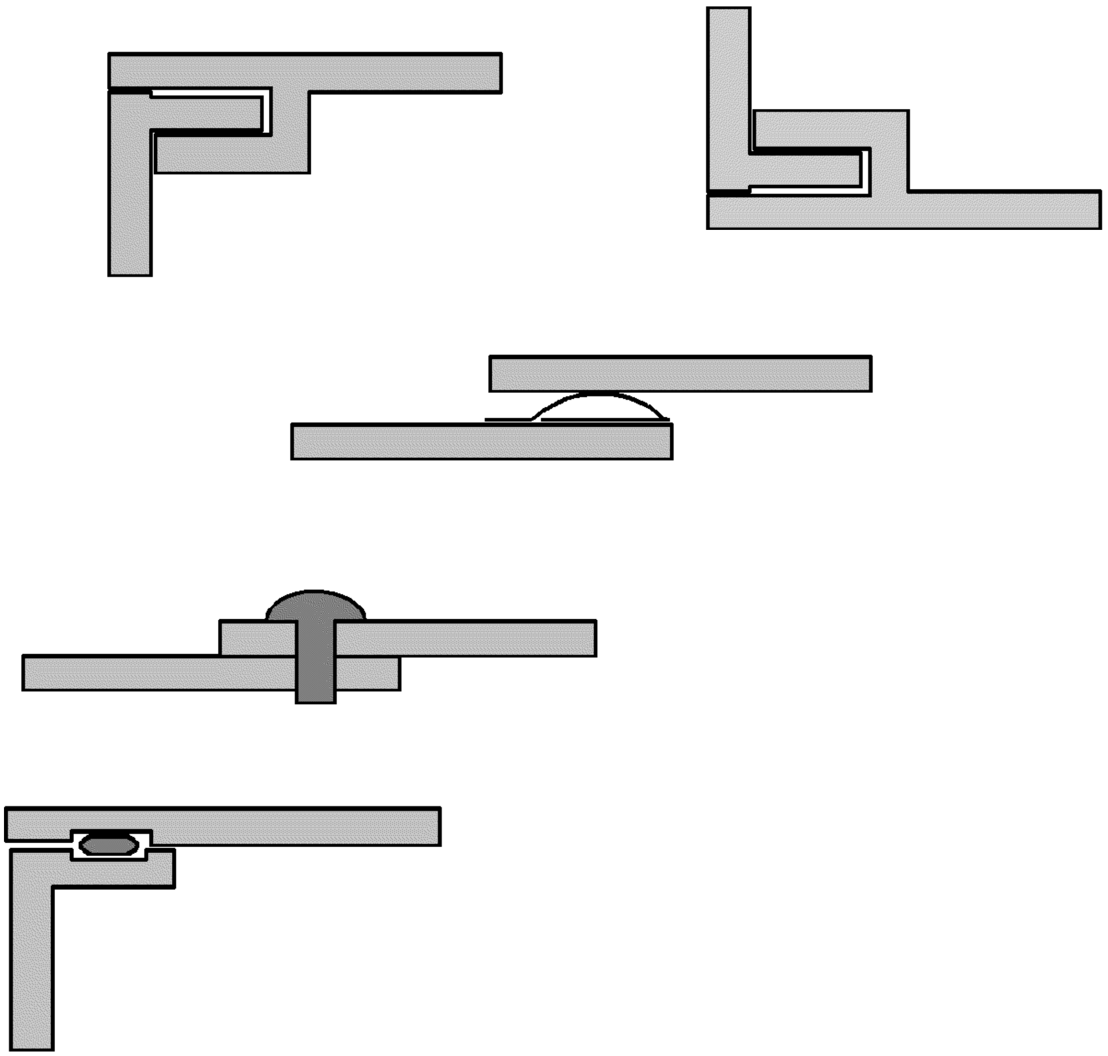
- Good metal-to-metal contact is essential
  - RF gaskets on all seams and penetrations
  - 360° termination of shield to backshell **(NO PIGTAILS!!!)**
  - Good metal-to-metal contact between backshell and chassis
    - Good metal-to-metal contact is essential to minimize ΔV and I_{CM} between surfaces
- Non-conductive coatings must be avoided
- Must be considered in conjunction with thermal requirement
- **Class R bonds**



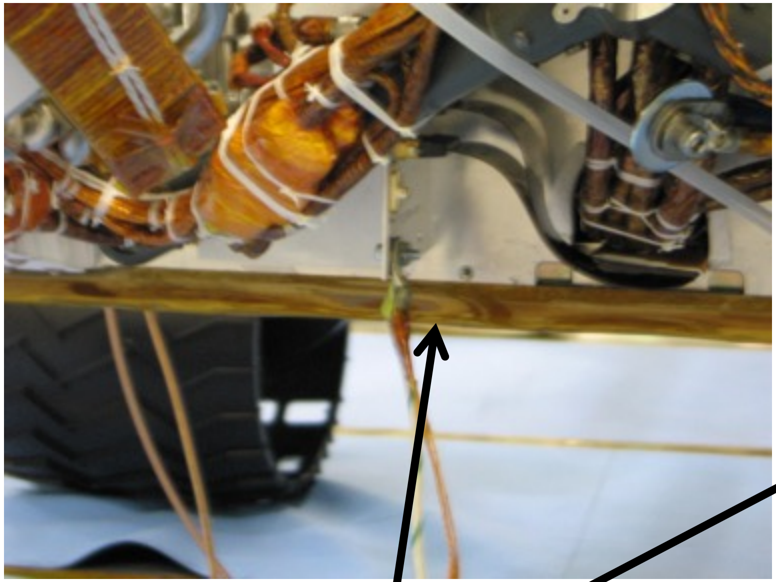
Courtesy of John McCloskey, EMC Chief Engineer at NASA-GSFC

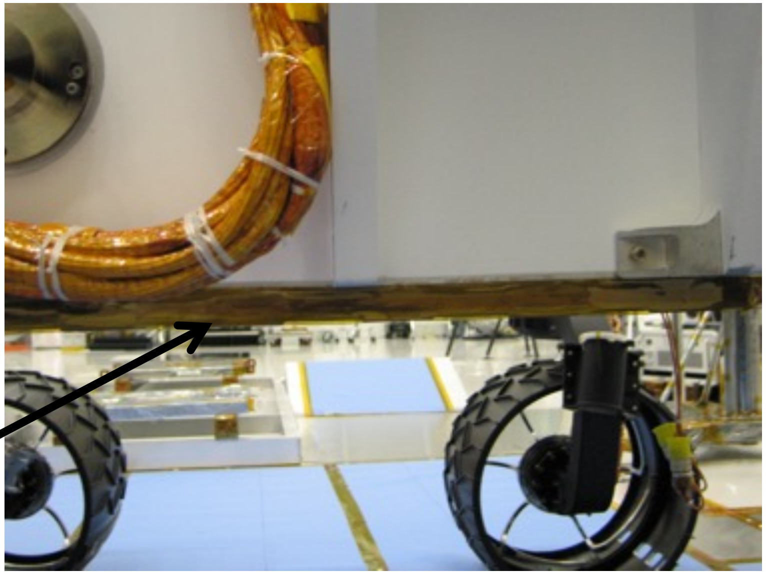
Shield Joints - Examples



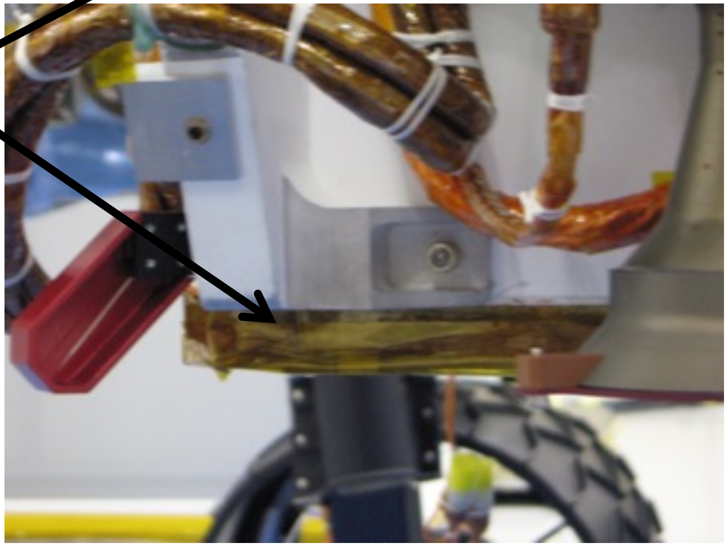


Rover Post-Bellypan RF Tape Install

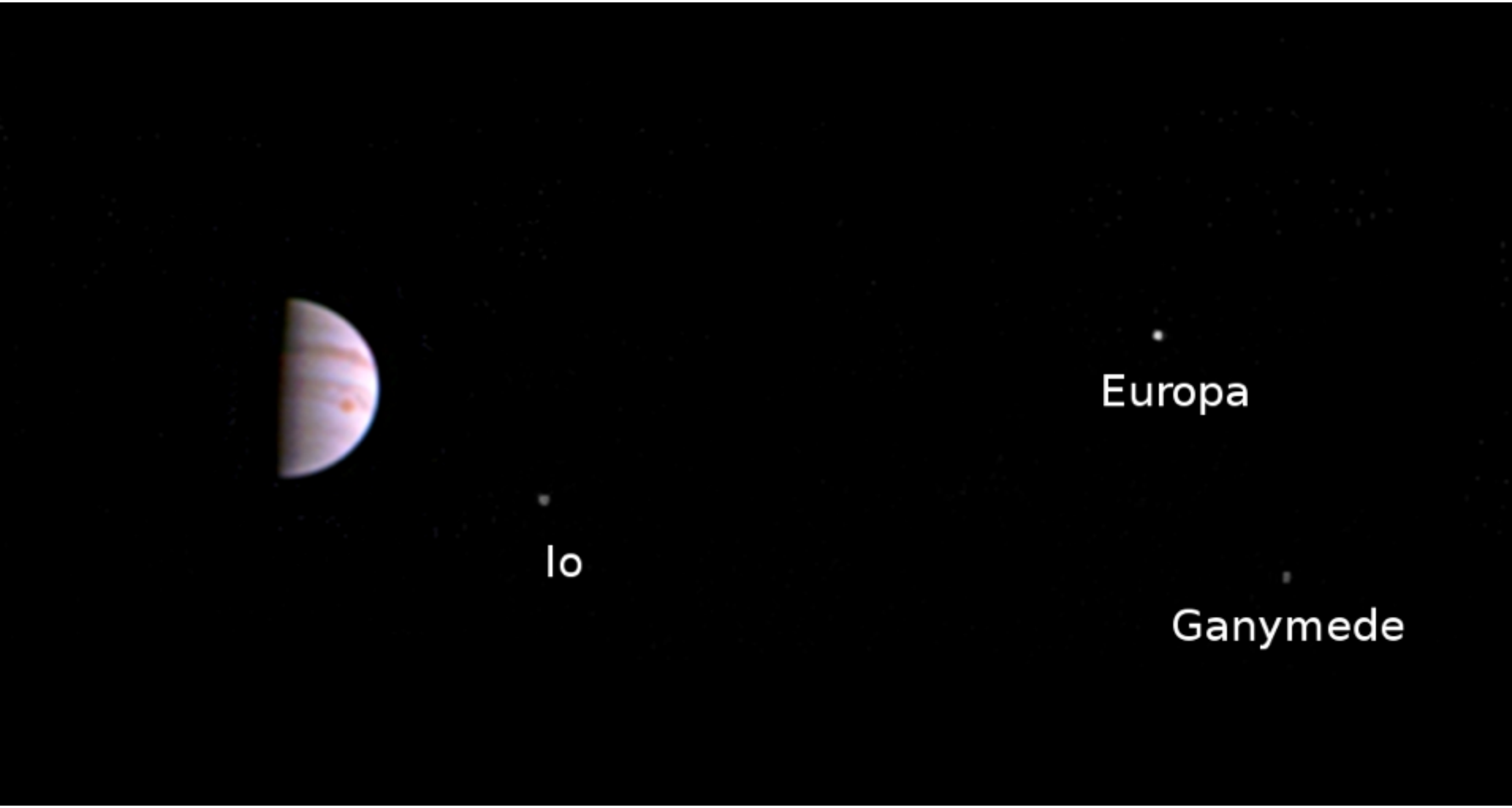




RF LAIRD CLOSE OUTS

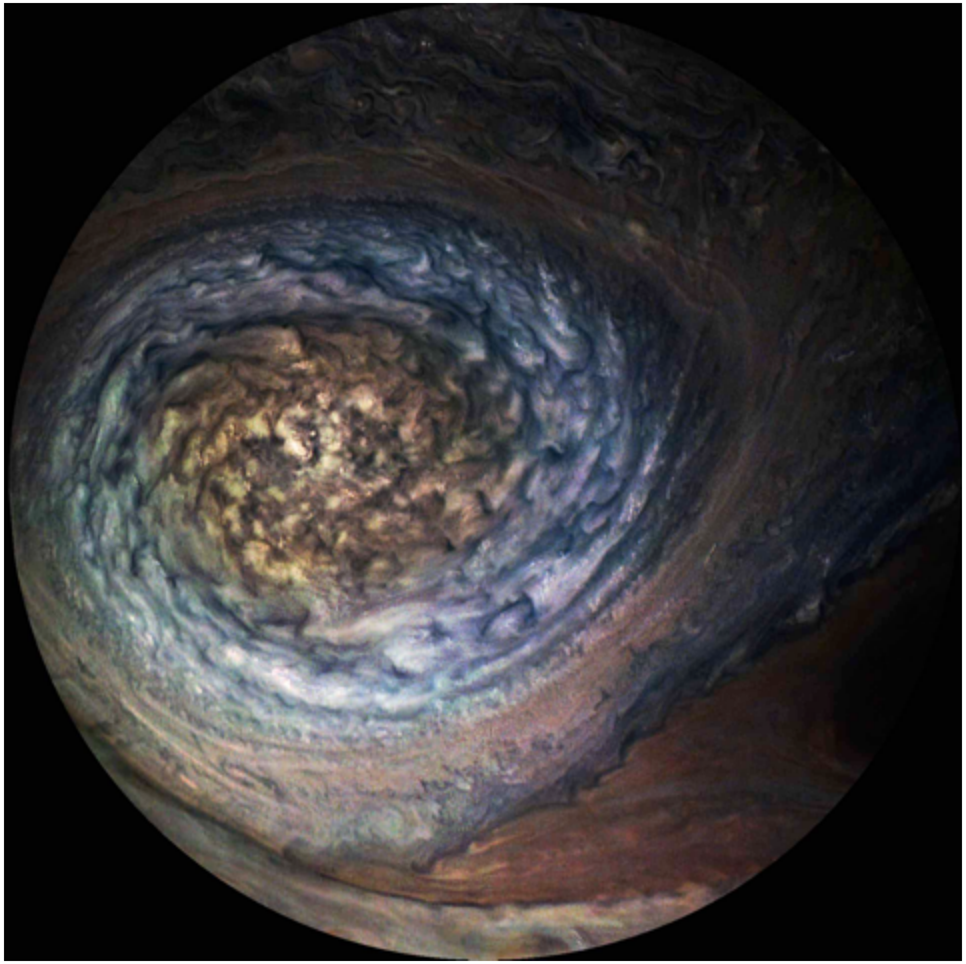


First Image From JUNO

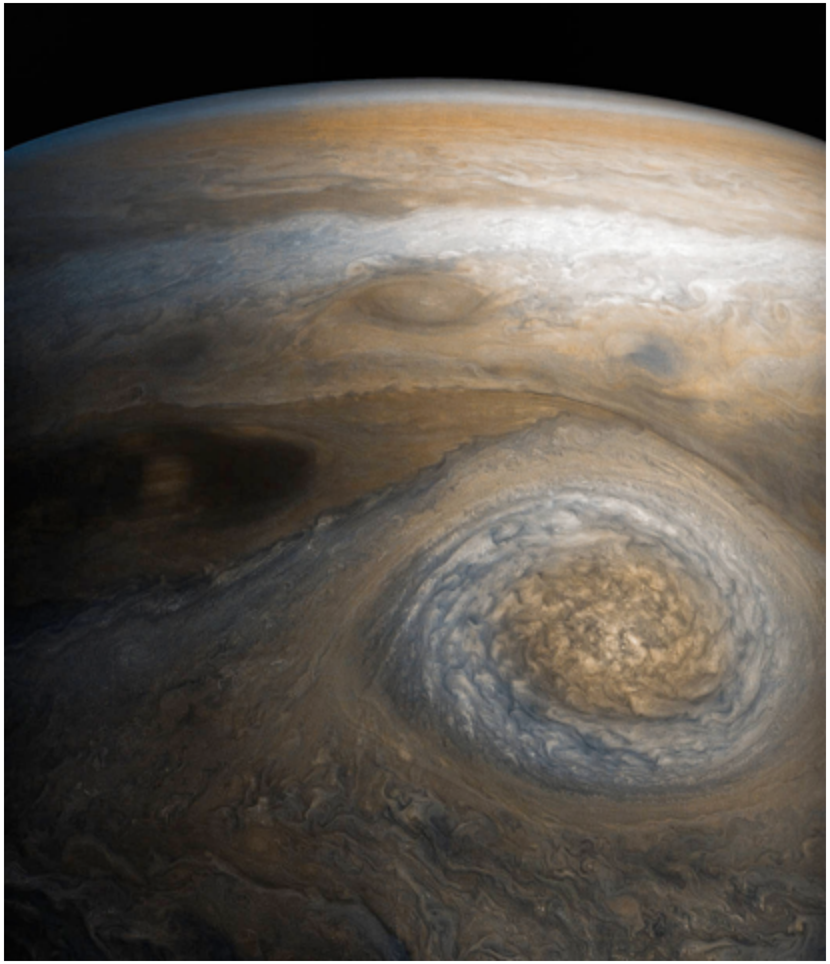


Courtesy of NASA-JPL

Close Up Images Of Jupiter

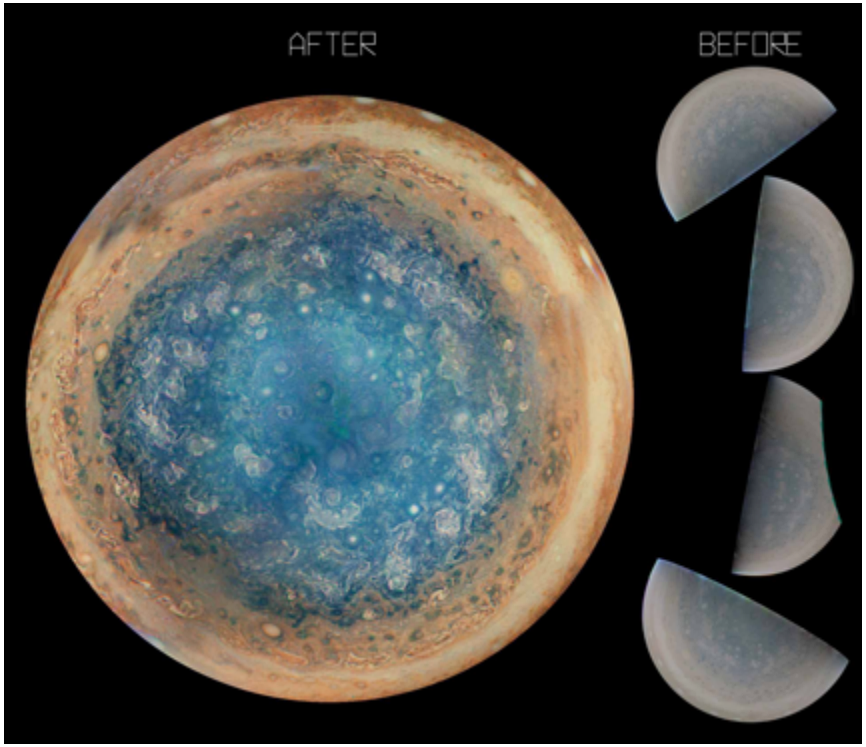


Courtesy of NASA-JPL



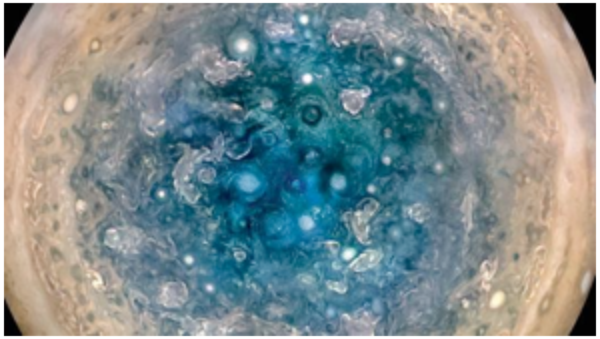
Courtesy of NASA-JPL

Images From JUNOCAM



Huge Cyclones at Jupiter’s Poles

Courtesy of NASA-JPL



Vincent Van Gogh

THANK YOU!